

WESTERN SYDNEY UNIVERSITY



EFFECTS OF LOW-FREQUENCY, LOW-ACCELERATION MOTION ON MANUAL TASK PERFORMANCE

by

Kwok-Shing Wong

Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

Western Sydney University

Sydney, Australia

2017

ACKNOWLEDGEMENTS

My studies on wind engineering commenced in 2003. At the beginning, I investigated the effects of wind-induced interference on tall buildings. Following that, I worked at the Wind/Wave Tunnel Faculty at the Hong Kong University of Science and Technology for five years. Until then, all my studies were conducted using various wind tunnel testing techniques. After working for five years, I recognised I needed a change.

Undertaking this research was a great change and challenge. Except for the criteria used for assessing the acceptability of wind-induced building motion, I knew nothing about this research topic which is associated with wind engineering, psychology, physiology, and human factors. I was totally new to psychology, physiology and human factors, which comprise a majority of the content of this research. Furthermore, my supervisors and I were working separately in Australia, New Zealand, and Hong Kong for most of the time. This increased the challenges to complete the research study. Fortunately, a lot of mentors, friends and funding bodies have continuously advised, improved, and supported me and this research to its completion. I take this chance to thank all of them.

Thank you to Professor Kenny Kwok for your tremendous support; from helping me complete the applications for scholarships, funding for attending conferences and purchasing equipment, to your guidance and critique on this thesis. Thank you very much for bringing me in to join this multi-disciplinary research team that comprises psychologists, physiologists, and engineers. My participation in this research has expanded my horizons by relating psychology and physiology with wind engineering. I particularly appreciate for your time and efforts in the last few months of preparing this thesis, especially spending time to have valuable Skype meetings with me. You often said, "Certain things don't change easily." This is true, Kenny, including my respect for you. My respect stems not only from your passion on wind engineering but also from your philosophy on taking care of students. Although you said you are an impatient person, I experienced how patient you are via your guidance throughout my entire PhD study. Thank you very much.

Thank you to Professor Vaughan Macefield for teaching me the physiological technique to measure and analyse muscle activity, as presented in this thesis, and encouraging me to express my thoughts. I admire your passion for physiology. You are the first person to show me how to conduct a physiological experiment on yourself by inserting a needle microelectrode through your skin. I also appreciate your “smooth talk” to calm down the nervous participants who were scared of inserting the needle microelectrode. I have never seen you fail. Your speed in writing and publishing journal papers is amazing. I wonder how you can make it happen. One thing that surprised me is you also like the music of Radiohead. Unbelievable!

Thanks also to Dr Darren Walton. You have showed me how to tackle a problem from different points of view. Your encouragement always supported me to move forward, particularly when I was struggling with how to proceed in my research. I recall the few days in April 2015 when you were visiting Hong Kong. You, Kenny and I were having a meeting in a restaurant. We analysed and discussed my experiment data, the results of the analyses then became the backbone of this thesis. I also thank you very much for making time to have Skype meetings with me in your busy schedule.

Thanks also to Professor Ravi Goonetilleke for your suggestions on aspects of human performance. You gave me a lot of ideas in the initial stages of this thesis, in particular the Fitts’ Law task experiment. Although results of the Fitts’ Law task experiment were not included in this thesis, designing and conducting the task experiment was excellence research experience.

There are a number of friends I would also like to thank. Dr. Peter Hitchcock, Dr. Tim Tse, and Dr. Ben Chan who have shared their experiences on conducting research and writing a PhD thesis. Dr. Elie Hamman, thank you very much for sharing your experience on physiological studies and commenting on the physiological aspect of this thesis; thanks also for introducing me to traditional Lebanese food in Sydney. A special thanks to Dr. Steve Lamb. Your comments on my Confirmation of Candidature document and this thesis were valuable. I will remember your assistance on writing and the time we spent on preparing a journal paper in Wellington.

Thanks to Professor C.M. Chan, Professor Y.K. Tung, and other staff at the Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology for ensuring the use of the motion simulator and office space, and managing the financial issues for subject recruitments and student helpers. Special thanks to Mr. David Leung, Mr. Michael Wu, Mr. Hor-Fong Yung, Mr. Sui-Ki Ngan, and Mr. Cheuk-Leung Tam, who ensured the motion simulator worked properly. Thanks to the participants. This thesis could not have been completed without their participation.

Thank you to the current and former professors, staff, and students of the Centre for Infrastructure Engineering, previously called the Institute for Infrastructure Engineering (IIE). Your cheers and supports while I was representing the IIE to participate in the Three-minute thesis competition are memorable. Special thanks to Professor Bijan Samali, Miss Magdalene Wong-Borgefjord, Miss Pauline Shaw, Dr. Mithra Fernando, and Mr. Nathan McKinlay for their support in administrative and technical issues.

Thanks to Dr Susan Mowbray, Academic Literacy Advisor at the Graduate Research School at Western Sydney University for your professional input on this thesis within a very short period of time.

This thesis was mainly supported by the International Postgraduate Research Scholarships (IPRS) and Australian Postgraduate Award (APA) funded by the Australian Government and partly by the Australian Research Council Discovery Project through the University of Western Sydney. The Centre for Infrastructure Engineering also provided funding for purchasing equipment, attending conferences and research meetings, and for the continuation of this PhD study.

One of the most important avenues of support for completing this thesis was my parents and all of my other family members. Your love and encouragement throughout my life are invaluable. I would encourage the next generation of my family to pursue breakthroughs throughout their lives.

STATEMENT OF AUTHENTICATION

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

.....

(Signature)

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	I
STATEMENT OF AUTHENTICATION	IV
TABLE OF CONTENTS	V
LIST OF TABLES	XI
LIST OF FIGURES	XIII
ABBREVIATIONS	XXI
ABSTRACT	XXII
PUBLICATIONS IN SUPPORT OF THIS THESIS	XXV
CHAPTER 1 INTRODUCTION	1
1.1 Research aims of this thesis	3
1.2 Thesis layout	4
CHAPTER 2 HUMAN RESPONSES TO LOW-FREQUENCY, LOW-ACCELERATION MOTION	6
2.1 Introduction	6
2.2 Perception thresholds under low-frequency, low-acceleration motion conditions	7
2.2.1 Field studies and surveys of occupants conducted in buildings subjected to strong wind	8
2.2.1.1 Summary	16
2.2.2 Perception thresholds determined in buildings subjected to artificial excitations	17
2.2.3 Using motion simulators	18
2.2.3.1 Summary	30
2.3 Manual task performance under low-frequency, low-acceleration motion conditions	30
2.3.1 Summary	41
2.4 Continuous tracking task performance under other types of motion conditions	42
2.4.1 Summary	48
2.5 Incidence of motion sickness or mild motion sickness in low frequency, low acceleration conditions	50
2.5.1 Summary	57
2.6 Sopsite syndrome	58
2.6.1 Summary	63
2.7 Postural control of standing human	64
2.7.1 Maintaining an upright posture	65
2.8 Criteria or recommendations for occupant response to wind-induced building motion	69
2.8.1 Summary	85
2.9 Concluding remarks	86

CHAPTER 3 METHODOLOGY FOR INVESTIGATION OF EFFECTS OF LOW-FREQUENCY, LOW-ACCELERATION MOTION ON MANUAL TASK PERFORMANCE 90

3.1 Introduction	90
3.2 Specifications of the motion simulator	91
3.3 Calibrations of the motion simulator	94
3.4 Experiment protocol for measuring manual task performance, sopite syndrome severity, and EMG signals	104
3.4.1 Participants	104
3.4.2 Continuous tracking task	105
3.4.3 Motion characteristics	108
3.4.4 Measures of motion sickness and sopite syndrome	112
3.4.5 A computer-based data acquisition and analysis system for EMG measurement	113
3.4.5.1 Laptop computer	114
3.4.5.2 Data acquisition hardware	115
3.4.5.3 High performance differential biological amplifiers (Bio Amps)	116
3.4.5.4 Cables	116
3.4.5.5 Surface electrode	117
3.4.6 Experimental procedure	118
3.5 Concluding remarks	127

CHAPTER 4 EFFECTS OF LOW-FREQUENCY, LOW-ACCELERATION MOTION ON PERFORMANCE OF A CONTINUOUS TRACKING TASK 128

4.1 Introduction	128
4.2 Method	130
4.3 Analysis	130
4.3.1 Dependent measures	130
4.3.1.1 Mean resultant distance	132
4.3.1.2 Standard deviation resultant distance	132
4.3.1.3 Maximum resultant distance	133
4.3.2 Exploratory data analysis	135
4.3.2.1 Three-dimensional surface plot	135
4.3.2.2 Box plot	135
4.3.3 Statistical analysis	136
4.3.3.1 Effects of motion	137
4.3.3.2 Effects of acceleration and frequency	137
4.3.3.3 Effects of gender and motion direction	137
4.3.3.4 Difference between static conditions	138
4.4 Results	138
4.4.1 Exploratory data analysis	138
4.4.1.1 Three-dimensional surface plot	138
4.4.1.2 Box plots	140
4.4.2 Statistical analysis on mean resultant distance	145
4.4.2.1 Effects of 8 milli-g motion	145
4.4.2.2 Effects of frequency and acceleration	145
4.4.2.3 Effects of gender	147
4.4.2.4 Effects of motion direction	147
4.4.2.5 Difference between static conditions	147

4.4.3 Statistical analysis on standard deviation resultant distance	147
4.4.3.1 Effects of 8 milli-g motion	147
4.4.3.2 Effects of frequency and acceleration	148
4.4.3.3 Effects of gender	149
4.4.3.4 Effects of motion direction	149
4.4.3.5 Difference between static conditions	150
4.4.4 Statistical analysis on maximum resultant distance	150
4.4.4.1 Effects of 8 milli-g motion	150
4.4.4.2 Effects of frequency and acceleration	150
4.4.4.3 Effects of gender	151
4.4.4.4 Effects of motion direction	151
4.4.4.5 Difference between static conditions	152
4.5 Discussion	152
4.5.1 Effects of motion on average accuracy, fluctuation, and maximum excursion of CTT performance	153
4.5.2 Effects of acceleration and frequency on CTT performance	154
4.5.3 Potential causes of motion-induced performance degradations	157
4.5.3.1 Increase in inertial force	157
4.5.3.2 Frequency response characteristics of an upright human body	159
4.5.4 Relative contribution on degradation of CTT performance between acceleration and frequency	161
4.5.5 Implications on criteria and recommendations for occupant response to wind-induced building motion	163
4.5.6 Effects of other factors on task performance	166
4.5.7 Effect of gender and motion direction on task performance	168
4.6 Limitations	168
4.7 Conclusions	169

CHAPTER 5 EFFECTS OF SOPITE SYNDROME ON A CONTINUOUS TRACKING TASK PERFORMED UNDER LOW-FREQUENCY, LOW-ACCELERATION MOTION CONDITIONS **171**

5.1 Introduction	171
5.2 Methodology	172
5.3 Analysis	173
5.3.1 Changes in motion sickness scores due to exposure to low-frequency, low-acceleration motion	173
5.3.2 Grouping of participants in accordance with changes in motion sickness scores	174
5.3.3 Effects of motion sickness on CTT performance under motion conditions	174
5.4 Results	174
5.4.1 Effects of exposure to low-frequency, low-acceleration motion on changes in MSAQ overall motion sickness and subscale scores	174
5.4.2 Effects of motion direction on changes in MSAQ overall motion sickness and subscale scores	176
5.4.3 Effects of gender on changes in MSAQ overall motion sickness and subscale scores	177
5.4.4 Grouping of participants based on sopite relate subscale score	177
5.4.5 Effects of sopite-related subscale score on mean resultant distance – average CTT performance	179

5.4.6 Effects of sopite-related subscale score on standard deviation resultant distance – fluctuation of CTT performance	182
5.4.7 Effects of sopite-related subscale score on maximum resultant distance – maximum excursion of CTT performance	185
5.4.8 Grouping of participants based on central subscale score	187
5.4.9 Effects of central subscale score on CTT performance under motion conditions	189
5.4.10 Participants who withdrew from the study due to severe motion sickness symptoms	190
5.5 Discussion	193
5.5.1 Exposure to low-frequency, low-acceleration motion provokes sopite syndrome	193
5.5.2 Effects of sopite syndrome on task performance	195
5.5.3 Effects of gender and motion direction on sopite syndrome severity	200
5.6 Limitations	201
5.7 Conclusions	202

CHAPTER 6 EFFECTS OF LOW-FREQUENCY, LOW-ACCELERATION FORE-AFT MOTION ON A CONTINUOUS TRACKING TASK – A HUMAN PHYSIOLOGICAL PERSPECTIVE 204

6.1 Introduction	204
6.2 Methodology	206
6.3 Analysis	207
6.3.1 Quantifying activation levels of leg muscles	207
6.3.2 Normalised standard deviation electromyographic signal	207
6.3.3 Statistical analysis	208
6.3.3.1 Effects of performing the CTT, acceleration, and frequency on the activation levels of leg muscles	208
6.3.3.2 Effects of symptoms of sopite syndrome on activation levels of leg muscles	209
6.4 Results	209
6.4.1 Soleus EMG	209
6.4.1.1 Main effect of performing CTT	210
6.4.1.2 Main effect of acceleration	212
6.4.1.3 Main effect of frequency	213
6.4.1.4 Interaction effect between frequency and performing the CTT	215
6.4.1.5 Interaction effect between acceleration and frequency	216
6.4.2 Tibialis anterior EMG	216
6.4.2.1 Main effect of performing CTT	217
6.4.2.2 Main effect of acceleration	218
6.4.2.3 Main effect of frequency	219
6.4.2.4 Interaction effect between acceleration and performing the CTT	220
6.4.2.5 Interaction effect between acceleration and frequency	221
6.4.3 Motion sickness subscale scores and grouping of participants based on sopite-related subscale score	222
6.4.4 Effects of sopite syndrome on normalised standard deviation EMG signals of leg muscles	223
6.4.4.1 Without performing CTT	224
6.4.4.2 Performing CTT	225

6.4.5 Effects of sopite syndrome on CTT performance under low-frequency, low-acceleration fore-aft motion conditions	227
6.5 Discussion	232
6.5.1 Evidence for compensatory action	233
6.5.1.1 Effects of performing CTT	233
6.5.1.2 Interaction between performing the CTT and frequency on activation level of SOL	234
6.5.1.3 Interaction between performing the CTT and acceleration on activation level of TA	235
6.5.2 Evidences for increased inertial forces – effects of acceleration on activation levels of SOL and TA	236
6.5.3 Evidence for resonant characteristic of human body – effects of frequency on activation levels of SOL and TA	237
6.5.4 Interaction between acceleration and frequency	237
6.5.5 Relationship between activation levels of leg muscles, symptoms of sopite syndrome, and CTT performance	238
6.5.6 Limitations	240
6.6 Conclusions	241
CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS	244
7.1 Conclusions	244
7.2 Recommendations for future work	249
7.2.1 Minimum acceleration magnitudes that degrade manual task performance	250
7.2.2 Manual task performance degradation contours for various probability levels	252
7.2.3 Effects of low-frequency, low-acceleration motion on other manual tasks	253
7.2.4 Relationships between manual task performance, sopite syndrome severity, and motion characteristics	254
7.2.5 Effects of narrow-band random motion on manual task performance and incidence of sopite syndrome	256
7.2.6 Body sway measurements	258
7.2.7 Reproduce the manual task performance investigation in wind-excited buildings	260
7.2.8 Participants	261
7.3 Concluding remarks	261
REFERENCE	263
APPENDIX A GENERAL INFORMATION FORM	276
APPENDIX B MOTION SICKNESS ASSESSMENT QUESTIONNAIRE (MSAQ)	277
APPENDIX C CHANGES IN MOTION SICKNESS ASSESSMENT QUESTIONNAIRE SOPITE-RELATED AND CENTRAL SUBSCALE SCORES	278

APPENDIX D MOTION SICKNESS SUBSCALE SCORES OF PARTICIPANTS COMPLETED CTT UNDER FORE-AFT MOTION CONDITIONS	280
APPENDIX E GROUPING OF PARTICIPANTS COMPLETED CTT UNDER FORE-AFT MOTION CONDITIONS BASED ON SOPITE RELATE SUBSCALE SCORE	282

LIST OF TABLES

Table 2.1. Perception thresholds and motion frequencies determined from three control towers by Denoon (2000).....	15
Table 2.2. Motion direction, frequency, and number of participants used in manual dexterity performance tests performed by Irwin and Goto (1984).	32
Table 2.3. Wind speed ranges of the high, medium, and low wind conditions.	55
Table 2.4. Guidelines for evaluation acceptability of wind-induced building motion proposed by Isyumov (1993, 1995).	80
Table 3.1. A summary of calibration results of all tested motion conditions.	97
Table 3.2. Static and motion conditions of an experimental session.	125
Table 3.3. An example of presentation order of all static and motion conditions of an experimental session.	126
Table 5.1. Changes of mean and standard deviation of all subscale scores due to exposure to low-frequency, low-acceleration motion.....	175
Table 5.2. Mean and standard deviation of average CTT performance of the low, medium, and high sopite syndrome groups.	180
Table 5.3. Mean and standard deviation of fluctuation of CTT performance of the low, medium, and high sopite syndrome groups.	182
Table 5.4. Mean and standard deviation of maximum excursion of CTT performance of the low, medium, and high sopite syndrome groups.	186
Table 5.5. Motion conditions and CTT accuracy immediately before withdrawing from the experiment; comparison of performance in the main sample measured under the same motion conditions.	192
Table 6.1. A summary of a three-way repeated-measures ANOVA on SOL EMG _{SD}	210
Table 6.2. Mean and standard deviation of SOL EMG _{SD} , with and without performing CTT.	211
Table 6.3. Mean and standard deviation of SOL EMG _{SD} across acceleration.....	213

Table 6.4. Mean and standard deviation of SOL EMG _{SD} across frequency.	214
Table 6.5. A result summary of a three-way repeated-measures ANOVA on TA EMG _{SD}	217
Table 6.6. Mean and standard deviation of TA EMG _{SD} when participants were or were not performing CTT.	218
Table 6.7. Mean and standard deviation of TA EMG _{SD} across acceleration.	219
Table 6.8. Mean and standard deviation of TA EMG _{SD} across frequency.	220
Table 6.9. A summary of main and interaction effects of sopite syndrome level on SOL EMG _{SD} of a mixed-design three-way ANOVA. Normalised SOL EMG _{SD} were measured when participants (N = 20) were not performing CTT.	224
Table 6.10. A summary of main and interaction effects of sopite syndrome level on normalised TA EMG _{SD} of a mixed-design three-way ANOVA. Normalised TA EMG _{SD} were measured when participants (N = 20) were not performing CTT.	224
Table 6.11. A summary of main and interaction effects of sopite syndrome severity on normalised EMG _{SD} of SOL and TA of mixed-design three-way ANOVAs. Normalised EMG _{SD} of SOL and TA were measured when participants (N = 20) were performing CTT.	225
Table 6.12. A result summary of main and interaction effects of sopite syndrome severity on CTT performance of mixed-design three-way ANOVAs.	228
Table 6.13. Mean and standard deviation values of CTT performance of low and high sopite syndrome severity group participants.	231
Table C.1 Changes of Motion Sickness Assessment Questionnaire (MSAQ) sopite-related subscale score of all test participants.	278
Table C.2 Changes of Motion Sickness Assessment Questionnaire (MSAQ) central item score of all test participants.	279
Table D.1 A summary of statistical results of the one-way repeated-measures ANOVAs on changes in motion sickness subscale scores.	280

LIST OF FIGURES

Figure 2.1. The highest peak acceleration of about 43 milli-g recorded at the top of the Allied Bank Plaza building in Houston during Hurricane Alicia in August of 1983 (reproduced from Isyumov et al., 1988).	13
Figure 2.2. Motion perception thresholds (reproduced from Burton et al., 2011).	29
Figure 2.3. Performance of tracing tasks across frequency (reproduced from Figure 25 of Irwin and Goto, 1984).	33
Figure 2.4. Examples of resultant acceleration time histories of bi-directional, narrow-band random motion (reproduced from Figure 2 of Burton et al., 2011).	38
Figure 2.5. Percentage of participants affected by motion (reproduced from Figure 4 of Burton et al., 2011).	51
Figure 2.6. A questionnaire used to evaluate each individual for symptoms of nausea and sopite syndrome during transport (reproduced from Table 1 of Wright et al., 1995).	59
Figure 2.7. A conceptual model describing the evolution of cognitive performance over time for asymptomatic and symptomatic participants in the 1st and 2nd experimental session (reproduced from Figure 4 of Matsangas et al., 2014).	62
Figure 2.8. (Left) Tibialis anterior muscle and surrounding structures. This is a view of the front of the right leg (reproduced from Gray, 1918). (Right) Soleus muscle and surrounding structures. This is a view of the back of the right leg; most of the gastrocnemius muscle has been removed (reproduced from Gray, 1918).	66
Figure 2.9. Winter (1995) has used this figure to show, in five different points in time, variations of distance between centre of gravity (COG) and the ankle (g), distance between centre of pressure (COP) locations and the ankle (p), angular accelerations (α), and angular velocity (ω) of an individual swaying back and forth while standing quietly (modified based on a figure reproduced from Winter, 1995, p. 195).	67
Figure 2.10. Maximum RMS acceleration of storm-induced horizontal motion suggested for buildings used for general purposes (Curve 1) and for offshore structures for non-routine duties and bridges (reproduced from Figure 2 of Irwin, 1978).	72
Figure 2.11. RMS acceleration magnitudes of perception to horizontal and vertical motion, that is, the horizontal base curve and the vertical base curve (reproduced from Figure 3 of Irwin, 1978).	74

Figure 2.12. Suggested satisfactory magnitudes of horizontal motion of buildings used for general purposes (curve 1) and of off-shore fixed structures (curve 2) (reproduced from Figure 1 of International Organization for Standardization, 1984).....	76
Figure 2.13. Lower (curve 1) and average (curve 2) perception thresholds of horizontal motion (reproduced from Figure 2 of International Organization for Standardization, 1984).	77
Figure 2.14. Acceleration magnitudes for various perception probabilities suggested in AIJ-GEH-2004 (reproduced from Figure 1 of Nakamura et al., 2004).	82
Figure 2.15. Peak acceleration curves suggested for evaluating the acceptability of wind-induced building motion with a return period of one year for office (curve 1) and residential (curve 2) buildings (reproduced from Figure D.1 of International Organization for Standardization, 2007).....	83
Figure 3.1. A schematic diagram of the test platform of the motion simulator at the Hong Kong University of Science and Technology (HKUST).	92
Figure 3.2. Capability of motion simulator at HKUST (reproduced from Kwok and Hitchcock, 2008).	93
Figure 3.3. External view of motion simulator.	94
Figure 3.4. Internal view of motion simulator.	94
Figure 3.5. Experimental setup for displacement calibration.	95
Figure 3.6. A view of a laser light dot shining on the scale.	95
Figure 3.7. Correlations between input and output displacement peaks for x- and y-axes.....	98
Figure 3.8. Experimental setup for motion simulator displacement measurements ..	99
Figure 3.9. Power spectral density functions of input and output acceleration time histories at 0.125 Hz: Top) 8 milli-g; middle) 16 milli-g; and bottom) 30 milli-g..	100
Figure 3.10. Power spectral density functions of input and output acceleration time histories at 0.25 Hz: Top) 8 milli-g; middle) 16 milli-g; and bottom) 30 milli-g....	101
Figure 3.11. Power spectral density functions of input and output acceleration time histories at 0.5 Hz: Top) 8 milli-g; middle) 16 milli-g; and bottom) 30 milli-g.....	102
Figure 3.12. Power spectral density functions of input and output acceleration time histories at 1 Hz: Top) 8 milli-g; middle) 16 milli-g; and bottom) 30 milli-g.....	103

Figure 3.13. An illustration of the horizontal, vertical, and resultant distances between a laser light dot and target centre. The resultant distance was used as a measure for overall CTT performance evaluation.	106
Figure 3.14. A participant performing the CTT inside the motion simulator.	106
Figure 3.15. The digital video camera (Sony HDR-GW77VE) used to record laser light dot movement.	107
Figure 3.16. An x-y plot of a 64-second locus measured under a 0.5 Hz 30 milli-g fore-aft motion condition for a test participant.	108
Figure 3.17. Wind-induced force and response components defined based on a) wind axes and b) body axes (reproduced from Figure 5.1 of Tamura and Kareem (2014)).	109
Figure 3.18. Variables and mechanisms that are associated with crosswind response of structures (reproduced from Figure 6 of Melbourne (1975)).	110
Figure 3.19. Examples of alongwind, crosswind, and torsional building motion (reproduced from Isyumov, 1995). Note the distinct beats or “bursts” containing multiple cycles of relatively similar amplitude.	111
Figure 3.20. A schematic diagram of the computer-based data acquisition and analysis system.	114
Figure 3.21. A view of LabChart 7 Pro installed on a 15.4-inch MacBook Pro.	115
Figure 3.22. A PowerLab 16/35 of the computer-based data acquisition and analysis system (reproduced from “PowerLab ADInstruments,” n.d.).	115
Figure 3.23. A Bio Amp used for measuring EMG signals emanated from leg muscles (reproduced from “Bio Amps ADInstruments,” n.d.).	116
Figure 3.24. A Lead Shielded Bio Amp Cable (reproduced from “Bio Amp Cables ADInstruments,” n.d.).	117
Figure 3.25. Shielded lead wires (B/R/W, 3 pk) (reproduced from “Biopotential Electrodes and Lead Wires ADInstruments,” n.d.).	117
Figure 3.26. A 3M™ Red Dot™ Adult Solid Gel Electrode 2238 (3M™, USA)...	118
Figure 3.27. Locations of surface electrodes: Top) TA; Bottom) SOL. Red: White: Black are positive, negative and reference electrodes. Muscles and surrounding structure of TA and SOL can be referred to Figure 2.8.	120

Figure 3.28. A foot flexes downward toward the sole. The soleus (SOL) is contracted.	121
Figure 3.29. A foot flexes in an upward direction. The tibialis anterior (TA) is contracted.	121
Figure 3.30. A figure showing locations of medial malleolus and lateral malleolus (reproduced from “picture-of-the-ankle,” 2014).	122
Figure 3.31. A view of lower legs and feet while an individual stands on his heels.	123
Figure 3.32. A view of lower legs and feet while an individual stands on their toes.	123
Figure 4.1. Time histories of horizontal and vertical deviation and the corresponding resultant distance of a laser light dot locus.	131
Figure 4.2. Truncations of resultant distance time history measured under 0.125 and 0.5 Hz motion conditions.	134
Figure 4.3. Three-dimensional surface plot of average mean resultant distance.	139
Figure 4.4. Three-dimensional surface plot of average standard deviation resultant distance.	139
Figure 4.5. Three-dimensional surface plot of average maximum resultant distance.	140
Figure 4.6. Box plots of mean resultant distance measured under fore-aft and lateral motion conditions. On each box, the central mark is the median, lower and upper edges of the box are respectively the 25th and 75th percentiles, whiskers extend to the maximum and minimum data points not considered as outliers, and outliers (+), are plotted individually.	142
Figure 4.7. Box plots of standard deviation resultant distance measured under fore-aft and lateral motion conditions, as in Figure 4.6.	143
Figure 4.8. Box plots of maximum resultant distance measured under fore-aft and lateral motion conditions, as in Figure 4.6.	144
Figure 4.9. Average mean resultant distance (mean \pm S.E.) of all participants (N = 40) across frequency and acceleration compared with the embedded static condition.	146

Figure 4.10. Average standard deviation resultant distance (mean \pm S.E.) of all participants (N = 40) across frequency and acceleration compared with the embedded static condition.	149
Figure 4.11. Average maximum resultant distance (mean \pm S.E.) of all participants (N = 40) across frequency and acceleration compared with the embedded static condition.	151
Figure 4.12. Effect sizes of average, fluctuation, and maximum excursion of CTT performance.....	154
Figure 4.13. A comparison between the patterns of average accuracy of CTT performance and the acceleration magnification factor measured at the back by Burton et al. (2006).	160
Figure 4.14. An experimental setup used to investigate the resonant frequency of human body (reproduced from Figure 1 of Shin et al., 2006).....	161
Figure 4.15. Relative contributions to CTT performance degradation by acceleration and frequency.	162
Figure 4.16. Frequency response curve of under damped mechanical systems. Damping ratios vary from 0.1 to 0.4 of critical.	163
Figure 4.17. A comparison of manual task performance degradations against one-year return period acceleration design criteria (International Organization for Standardization, 2007). Numbers in boxes or on contour lines are ratios of CTT accuracy measured under a motion condition to static condition. The contours were extrapolated from the ratios determined for all motion conditions tested in the current study.	165
Figure 4.18. Effect sizes of acceleration, frequency, and other factors on mean resultant distance.....	167
Figure 5.1. MSAQ subscale scores (mean \pm S.E.) pre- and post- exposure to motion of all participants (N = 40).	176
Figure 5.2. Cumulative frequency distribution of change in sopite-related subscale score.	178
Figure 5.3. Changes in sopite-related subscale scores (mean \pm S.E.) across high (N = 12), medium (N = 12), and low (N = 16) sopite syndrome severity groups.	179
Figure 5.4. Average mean resultant distance (mean \pm S.E.) across high (N = 12), medium (N = 12), and low (N = 16) sopite syndrome severity groups.	180

Figure 5.5. Average mean resultant distance (mean \pm S.E.) across frequency grouped by sopite syndrome severity: high (N = 12), medium (N = 12), and low (N = 16).	181
Figure 5.6. Average mean resultant distance (mean \pm S.E.) across acceleration, grouped by sopite syndrome severity: high (N = 12), medium (N = 12), and low (N = 16).	181
Figure 5.7. Average standard deviation resultant distance (mean \pm S.E.) across high (N = 12), medium (N = 12), and low (N = 16) sopite syndrome severity groups.	183
Figure 5.8. Average standard deviation resultant distance (mean \pm S.E.) across frequency grouped by sopite syndrome severity: high (N = 12), medium (N = 12), and low (N = 16).	184
Figure 5.9. Average standard deviation resultant distance (mean \pm S.E.) across acceleration grouped by sopite syndrome severity: high (N = 12), medium (N = 12), and low (N = 16).	184
Figure 5.10. Average maximum resultant distance (mean \pm S.E.) across high (N = 12), medium (N = 12), and low (N = 16) sopite syndrome severity groups.	185
Figure 5.11. Average maximum resultant distance (mean \pm S.E.) across frequency grouped by sopite syndrome severity: high (N = 12), medium (N = 12), and low (N = 16).	186
Figure 5.12. Average maximum resultant distance (mean \pm S.E.) across acceleration grouped by sopite syndrome severity: high (N = 12), medium (N = 12), and low (N = 16).	187
Figure 5.13. Cumulative frequency distribution of change in central subscale score.	188
Figure 5.14. Change in central subscale score (mean \pm S.E.) across high (N = 12), medium (N = 12), and low (N = 16) sopite syndrome severity groups.	189
Figure 5.15. MSAQ subscale scores (mean \pm S.E.) of participants who withdrew from the lateral motion experiment (N = 4).	191
Figure 5.16. Attentional resource distributions of a participant performing the CTT under four operating cases. Case 1, under static condition with idle attentional resources and without appearance of sopite syndrome. Case 2, under motion conditions and performing CTT in an overloaded zone, idle attentional resources supply for balancing. Case 3, idle attentional resources are exhausted, attentional resources are diverted from hand-eye coordination and other processes to maintaining balance. Case 4, appearance of sopite syndrome withdraws attentional resources from hand-eye coordination, balancing, other processes, or a combination of them.	199

Figure 6.1. SOL EMG _{SD} (mean \pm S.E.) of participants (N = 20), with and without performing CTT. Performing CTT significantly increases SOL EMG _{SD}	211
Figure 6.2. SOL EMG _{SD} (mean \pm S.E.) of participants (N = 20) across acceleration. SOL EMG _{SD} increases as acceleration increases from 8 milli-g to 30 milli-g.	212
Figure 6.3. SOL EMG _{SD} (mean \pm S.E.) of participants (N = 20) across frequency. SOL EMG _{SD} shows a nonlinear relationship with frequency.....	214
Figure 6.4. SOL EMG _{SD} (mean \pm S.E.), with and without performing CTT, of participants (N = 20) across frequency.	215
Figure 6.5. SOL EMG _{SD} (mean \pm S.E.) of participants (N = 20) across frequency and separated in accordance with acceleration. The nonlinear relationship between SOL EMG _{SD} and frequency at 30 milli-g is the most prominent.	216
Figure 6.6. TA EMG _{SD} (mean \pm S.E.) measured when participants (N = 20) were or were not performing CTT.	218
Figure 6.7. TA EMG _{SD} (mean \pm S.E.) of participants (N = 20) across acceleration. TA EMG _{SD} increases as acceleration increases from 8 milli-g to 30 milli-g.....	219
Figure 6.8. TA EMG _{SD} (mean \pm S.E.) of participants (N = 20) across frequency. TA EMG _{SD} shows a nonlinear relationship with frequency.....	220
Figure 6.9. TA EMG _{SD} (mean \pm S.E.) of participants (N = 20) across acceleration and separated according to whether participants were or were not performing the CTT.	221
Figure 6.10. TA EMG _{SD} (mean \pm S.E.) of participants (N = 20) across frequency and separated according to acceleration. The nonlinear relationship between TA EMG _{SD} and frequency at 30 milli-g is the most prominent.	222
Figure 6.11. Normalised SOL EMG _{SD} (mean \pm S.E.) across high (N = 9) and low (N = 11) sopite syndrome severity groups. Participants were performing CTT.	226
Figure 6.12. Normalised TA EMG _{SD} (mean \pm S.E.) across high (N = 9) and low (N = 11) sopite syndrome severity groups. Participants were performing CTT.	227
Figure 6.13. Mean resultant distance (mean \pm S.E.) across high (N = 9) and low (N = 11) sopite syndrome severity groups under low-frequency, low-acceleration fore-aft motion conditions.....	229
Figure 6.14. Standard deviation resultant distance (mean \pm S.E.) across high (N = 9) and low (N = 11) sopite syndrome severity groups under low-frequency, low-acceleration fore-aft motion conditions.	230

Figure 6.15. Maximum resultant distance (mean \pm S.E.) across high (N = 9) and low (N = 11) sopite syndrome severity groups under low-frequency, low-acceleration fore-aft motion conditions.	230
Figure 7.1. An acceleration and frequency range proposed for further studies. (revised based on Figure 4.17).	251
Figure 7.2. Motion sickness incidence of three independent groups of individuals measured at 0.25 Hz and at RMS accelerations of 111, 222, and 333 milli-g across time (reproduced from Figure 7 of McCauley et al., 1976).	254
Figure 7.3. Motion sickness incidence as a function of acceleration and frequency (reproduced from Figure 8 of McCauley et al., 1976). Motion sickness incidence was defined as percentage of individuals vomiting within 2 hours of exposure to vertical sinusoidal motion.	255
Figure D.1 Pre-test and post-test sopite-related subscale scores (mean \pm S.E.) of participants (N = 20) performing the CTT.	281
Figure E.1 Cumulative frequency distribution of change in sopite-related subscale score of participants performing the CTT under fore-aft motion conditions.	282
Figure E.2 Sopite-related subscale score (mean \pm S.E.) of high (N = 9) and low (N = 11) sopite syndrome severity groups of participants performing CTT under fore-aft motion conditions.	283

ABBREVIATIONS

ANOVA: Analysis of Variance

ASCE: American Society of Civil Engineers

CTT: Continuous tracking task

CNS: Central nervous system

COG: Centre of gravity

COP: Centre of pressure

Cohen's *d*: Effect size; a standardised measure of a difference between two groups

DST: Digit Span Test

EMG_{SD}: Standard deviation of electromyographic signal

HKUST: The Hong Kong University of Science and Technology

M: Mean

MSAQ: Motion Sickness Assessment Questionnaire

N: Sample size

NASA: The National Aeronautics and Space Administration

p-value: The probability of incorrectly rejecting a true null hypothesis, a *p-value* of 5% was used in this thesis

RMS: Root-mean-square

SD: Standard deviation

S.E.: Standard error

SOL: Soleus

SRR: Slow Rotation Room

SSS: Stanford Sleepiness Scale

TA: Tibialis anterior

ABSTRACT

The current criteria and recommendations for assessing the acceptability of wind-induced building motion were largely established based on human perception thresholds and/or tolerance to wind-induced building motion. Therefore, they may not be able to ensure the performance of manual tasks is unaffected by wind-induced building motion. Few studies have investigated the effects of wind-induced building motion on manual task performance, and the findings of these studies are inconclusive. Hence the relationships between manual task performance and the wind-induced building motion and the mechanisms causing manual task performance degradation are yet to be explored and fully understood. Sospite syndrome describes a set of symptom centering around drowsiness due to exposure of healthy individuals to real or apparent motion. Recent studies have shown that symptoms of sospite syndrome are the most frequent manifestations of the effects of wind-induced building motion and decrease subjective work performance and objective cognitive task performance of building occupants. However, no study has investigated the effects of sospite syndrome on manual task performance.

This thesis investigates the effects of low-frequency, low-acceleration motion and sospite syndrome on manual task performance based on a series of motion simulator experiments. Twelve low-frequency, low-acceleration motion conditions were generated using four frequencies (0.125, 0.25, 0.5, and 1 Hz) and three acceleration magnitudes (8, 16, and 30 milli-g) for both fore-aft and lateral directions. A continuous tracking task (CTT) was used as a paradigm to investigate the effects of the motion on manual task performance. Aiming accuracy of the CTT is the dependent measure. Twenty (10 males and 10 females) participants completed the experiment under fore-aft motion conditions and another 20 participants (10 males and 10 females) under lateral motion conditions. A Motion Sickness Assessment Questionnaire (MSAQ) was used to measure motion sickness severity, in particular sospite syndrome severity, of the participants before and after the exposure to the motion conditions. Activation levels of soleus (SOL) and tibialis anterior (TA), the lower leg muscles involved in maintaining balance in the fore-aft direction, were measured using electromyography (EMG) to provide supporting evidences for the effects of motion and sospite syndrome on manual task performance from a physiological perspective.

Both acceleration and frequency were found to contribute to the degradations of manual task performance. Acceleration shows a strong inverse relationship with manual task performance; manual task performance decreases as the acceleration increases from 8 milli-g to 30 milli-g. The acceleration effect is attributable to an increase in inertial force. The activation levels of the SOL and TA also increase as acceleration increases from 8 milli-g to 30 milli-g. Evidently, the increase in inertial force can, in turn, induce visual impairment, disrupt balance, increase vibration breakthrough, and/or trigger motion sickness or sopite syndrome.

In contrast, frequency has a complex nonlinear relationship with manual task performance. The worst manual task performance was measured at 0.5 Hz among the test frequencies ranging from 0.125 Hz to 1 Hz. This frequency effect is associated with the frequency response characteristic of the human body. Body sway increases as frequency approaches the resonant frequency of a standing human, which occurs at near 0.5 Hz. The activation levels of SOL and TA increase as frequency increases from 0.125 Hz to approximately 0.5 Hz, then drop as frequency increases from 0.5 Hz to 1 Hz. This affirms that the body sways the most at 0.5 Hz. The increases in body sway can cause discomfort, divert attention resources from performing a manual task, and trigger anxiety that increases difficulty to response to manual tasks.

Symptoms of sopite syndrome were provoked in most participants due to the influence of approximately 30 minutes exposure to the 12 motion conditions. Manual task performance was found to have an inverse relationship with sopite syndrome severity: individuals who exhibited mild to severe sopite syndrome performed worse than relatively unaffected individuals. Sopite syndrome imposes discomfort and stress on affected participants and lowers their motivation to perform the manual task. Body sway in response to motion is further exacerbated for participants who exhibited sopite syndrome, causing postural instability that affected task performance. These adverse effects associated with sopite syndrome combined to degrade the manual task performance for affected participants. The activation levels of the lower leg muscles increased with sopite syndrome severity when the participants were performing the manual task. This suggested that participants suffering sopite syndrome actively intervened with higher activation levels of leg muscles to perform the manual task than the relatively unaffected participants. The conscious increase in activating leg muscles may distract and/or diverted attention from performing the manual task, further degrading the manual task performance.

Importantly, manual task performance was found to be degraded even at the lowest test acceleration magnitude of 8 milli-g. Acceleration of this magnitude may be considered satisfactory by the current criteria for assessing the habitability of wind-excited buildings, including ISO10137:2007. Therefore, current criteria do not ensure that the performance of manual tasks are unaffected by wind-induced building motion.

PUBLICATIONS IN SUPPORT OF THIS THESIS

Journal papers:

Wong, K.S., Lamb, S., Walton, D., Kwok, K.C.S., “Effects of Acceleration, Frequency and Mild Motion Sickness on Continuous Tracking Task Accuracy in Response to Simulated Wind-Induced Building Motion”, submitted to Journal of Wind Engineering and Industrial Aerodynamic, under review.

Conference and work shop presentations:

Kwok, K., Lamb, S., Wong, K.S., (2015). “Detrimental effects of wind-induced building motion on occupant work and task performance”, Implementing Innovative Ideas in Structural Engineering and Project Management: Proceedings of the 8th International Structural Engineering and Construction Conference (ISEC-8), Sydney, Australia, November 23-28, 2015

Wong, K.S., Hau C.L.V., Kwok, K.C.S., (2013). “Effects of wind-induced tall building vibrations on a tracking task”, Proceedings of 12th Americas Conference on Wind Engineering, Seattle, USA.

Wong, K.S., Hau, C.L.V., Kwok, K.C.S., Gonetilleke, R.S., (2013). “Effects of wind-induced tall building vibrations on human motor performance”, Proceedings of 6th European and African Conference on Wind Engineering, Cambridge, UK.

Kwok, K.C.S. and Wong, K.S. (2012). “A Dual-Axis Tall Building Motion Simulator to Investigate Effects of Wind-Induced Building Motions on Human”, Proceedings of 15th Australasian Wind Engineering Society Workshop, 23-24 February, Sydney, Australia.

Wong, K.S., (2012). “A Dual-Axis Tall Building Motion Simulator to Investigate Effects of Wind-Induced Building Motions on Human performances”, Abstracts of the Inaugural Research Futures Forum, 8 June, Sydney.

Wong, K.S., Hau, C.L.V., Kwok, K.C.S., (2012). “Effects of wind-induced tall building vibrations on human motor performance”, Proceedings of Inaugural Annual Conference of the Institute for Infrastructure Engineering, 30 November, Sydney.

CHAPTER 1

INTRODUCTION

Wind actions are important factors on the design of buildings, particularly in regions that are prone to strong wind events. Buildings with a fundamental natural frequency of 1 Hz or below are likely to be wind-sensitive (Australian Standard/New Zealand Standard, 2011). The aims of a building design for wind actions are to ensure the building is safe and remains functional under normal and extreme loading conditions. In some cases, while the design of a wind-sensitive building satisfies the strength requirements for safety and lateral drift requirements for the performance of structural and non-structural elements, the wind-sensitive building may still move excessively under wind actions. The excessive wind-induced building motion is sometimes perceptible, causing fear and discomfort to the building occupants. The excessive wind-induced building motion can also degrade wellbeing, work performance, cognitive task performance, and/or the manual task performance of the building occupants, hence degrading habitability of the buildings. Assessing the acceptability of wind-induced building motion in regard to building habitability is therefore a vital requirement in the design of buildings.

Evaluating the acceptability of wind-induced building motion has attracted the attention of engineers since the early 1930s. The American Society of Civil Engineering (ASCE) Structural Division's Sub-Committee No. 31 recommended "that structural frames be so designed as to insure (the author probably meant ensure) that deflections and vibrations will be kept within such limits as to render buildings comfortably habitable" (Coyle, 1931, p. 700). Over the last 50 years studies have been conducted to investigate the effects of wind-induced building motion on the habitability of buildings. A majority of the studies have focused on perception thresholds and/or tolerance to wind-induced building motion (for example Chen and Robertson, 1972; Goto, 1983; Hansen et al., 1973; Tamura et al., 2006). Based on the results of these studies, researchers have established criteria and recommendations for assessing the acceptability of wind-induced motion of buildings used for general purposes (for example Architectural Institute of Japan, 2004; International Organization for Standardization, 1984, 2007).

The criteria and recommendations were established largely based on perception thresholds and/or tolerance to wind-induced building motion. For example, “Bases for design of structures - Serviceability of buildings and walkways against vibration ISO 10137:2007” (International Organization for Standardization, 2007), the latest acceleration criteria, proposes a set of acceleration magnitude curves for assessing the acceptability of wind-induced building motion in residential and office buildings. The acceleration magnitude curve for residential buildings is close to the perception probability of 90% of the general public. The criteria however do not consider the effects of wind-induced building motion on wellbeing, work performance, cognitive task performance, and/or manual task performance. This raises/prompts the question, are these criteria sufficient for assessing the acceptability of wind-induced building motion regarding the habitable environment of a building?

Few studies have investigated the effects of wind-induced building motion on the performance of manual tasks (for example Burton et al., 2011; Goto et al., 1990; Irwin and Goto, 1984). Burton et al. (2011), for example, found variations of acceleration and/or frequency did not affect manual task performance. They suggested the neutral findings may be attributed to the actions of the young and fit participants who were able to compensate for the difficulty in maintaining balance. However, Burton et al. (2011) did not provide any evidence to support this suggestion. Since the performance of manual tasks carried out under motion conditions is highly associated with interruptions due to motion-induced body sway (Wertheim, 1998), Burton et al. (2011) suggestion of compensatory actions being associated with how an individual maintain balance under motion conditions is worthy of further study, particularly as first, other studies found that wind-induced building motion can degrade manual task performance (for example Goto et al., 1990) and second, the mechanisms that may have caused the manual task performance degradation were not explored and are yet to be fully understood and third, none of the previous studies established relationships between manual task performance and motion frequency and acceleration magnitudes. Furthermore, other studies generally suggested that perception thresholds decrease as frequency increases from 0.1 Hz to 1 Hz, recognising that perception to motion depends on motion frequency (for example Chen and Robertson, 1972; Kwok et al., 2009; Tamura et al., 2006). This prompts the further question as to whether manual task performance is also frequency dependent.

Studies investigating the effect of wind-induced building motion on incidents of motion sickness or mild motion sickness are also very limited. The majority of these studies indicate that wind-induced building motion can provoke salient symptoms of motion sickness, such as nausea and vomiting (for example Burton et al., 2005; Goto, 1983; Hansen et al., 1973). A recent study has shown that the effects of wind-induced building motion are “mostly manifest as symptoms of sopite syndrome” (Lamb et al., 2014, p. 39). Sopite syndrome is a form of mild motion sickness. It is a “symptom-complex centering around drowsiness” (Graybiel and Knepton, 1976, p. 873) due to exposure of healthy individuals to real or apparent motion. Sopite syndrome also includes symptoms such as lassitude, lethargy, mild depression, and reduced ability to focus on an assigned task (Matsangas and McCauley, 2014). Lamb et al. (2014) also showed that subjective work performance and cognitive performance of building occupants decreased as wind-induced building motion increased the severity of sopite syndrome. These findings suggest sopite syndrome may degrade manual task performance in wind-induced building motion environments. They also indicate the need for further research to better understand how wind-induced building motion may compromise the habitable working environment of a building.

1.1 Research aims of this thesis

Few studies have investigated the effects of low-frequency, low-acceleration motion, including wind-induced building motion, on the performance of manual tasks. To address the research gap, this thesis aims to:

- i) determine whether low-frequency, low-acceleration motion degrades manual task performance in the range of frequency and acceleration comparable to wind-induced building motion and, if it does,
- ii) explore how manual task performance is degraded as a function of motion frequency and acceleration,
- iii) determine the relative contributions of frequency and acceleration in the degradation,
- iv) explore the effects of gender on manual task performance,
- v) determine the effect of motion direction on manual task performance,

- vi) explore the implications of manual task performance degradation on the criteria and recommendations for the evaluation of occupant responses to wind-induced building motion,
- vii) determine the incidence of sopite syndrome due to exposure to the low-frequency, low-acceleration motion,
- viii) determine whether sopite syndrome affects manual task performance,
- ix) determine if any compensatory action was carried out in performing a manual task under low-frequency, low-acceleration motion conditions, and
- x) provide evidence, from a physiological perspective, to support the findings of the previous research aims.

1.2 Thesis layout

This thesis consists of seven chapters. The current chapter, Chapter 1, provides a brief introduction on the acceptability of wind-induced building motion and highlights the necessity of further investigations on the effects of low-frequency, low-acceleration motion on the manual task performance of occupants. It also establishes the scope of the thesis, as detailed below.

Chapter 2 examines studies investigating the effects of low-frequency, low-acceleration motion on the habitability of buildings subjected to wind actions. It emphasises the inadequacy of current understandings of the effects of low-frequency, low-acceleration motion on manual task performance. It also reviews previous studies that investigate the effects of other types of motion on manual task performance, providing insights for investigating the effects of wind-induced building motion on manual task performance.

Chapter 3 describes the methodology used to investigate the effects of low-frequency, low-acceleration motion on manual task performance. It details the design specifications and calibration results of the motion simulator at the Hong Kong University of Science and Technology (HKUST) used to produce the low-frequency, low-acceleration motion in this thesis.

Chapter 4 investigates the effects of low-frequency, low-acceleration motion on the performance of a manual task. In particular, the chapter focuses on the effects of frequency and acceleration on the performance of a manual task. It also demonstrates that ISO 10137:2007 (International Organization for Standardization, 2007), the latest acceleration criteria proposed for assessing the acceptability of wind-induced building motion in residential and office environments, is inadequate to ensure the performance of manual tasks is unaffected.

Chapter 5 investigates the effects of motion sickness on manual task performance. The severity of motion sickness of participants was measured using a Motion Sickness Assessment Questionnaire (MSAQ) (Gianaros et al., 2001). Participants were divided into different motion sickness severity groups to evaluate the effects of motion sickness on their manual task performance.

Chapter 6 provides evidence, from a physiological perspective, to support the findings in Chapters 4 and 5. It also provides insights into the compensatory actions that an individual may carry out to perform a manual task under low-frequency, low-acceleration motion conditions.

Chapter 7, as the concluding chapter, summarises the major findings of this thesis and provides recommendations for future work.

CHAPTER 2

HUMAN RESPONSES TO LOW-FREQUENCY, LOW-ACCELERATION MOTION

2.1 Introduction

Researchers have investigated effects of low-frequency, low-acceleration motion, including wind-induced building motion, on human responses over the past 50 years. The majority of the studies have focused on human perception thresholds to low-frequency, low-acceleration motion. This chapter first reviews studies on perception thresholds to motion, either in buildings or using a motion simulator in Section 2.2 . Many studies have investigated effects of motion on manual task performance in the field of transportation. In contrast, relatively little research has studied the effects of low-frequency, low-acceleration motion on manual task performance of occupants in wind-excited buildings and/or simulated wind-excited building environments. Although the motion used in the transportation studies is significantly different from low-frequency, low-acceleration motion, the transportation studies may provide insights into the effects on manual tasks under low-frequency, low-acceleration motion. Sections 2.3 and 2.4 respectively introduce studies on manual task performance under the effects of low-frequency, low-acceleration motion and a number of relevant studies that investigated effect of motion on manual task performance in transportation environments.

Few studies have investigated the incidence of motion sickness and/or sopite syndrome in low-frequency, low-acceleration motion environments. Recent studies show that symptoms of sopite syndrome are major manifestations of the effects of wind-induced building motion (Lamb et al., 2013, 2014; Walton et al., 2011). Sopite syndrome is a term used to describe a “symptom-complex centering around drowsiness” (Graybiel and Knepton, 1976, p. 873) due to exposure of healthy individuals to real or apparent motion. Sopite syndrome also includes symptoms such as lassitude, lethargy, mild depression, and reduced ability to focus on an assigned task (Matsangas and McCauley, 2014). Other studies show that the incidence of sopite syndrome also occurs in other type of motion environments (for example Lawson and Mead, 1998; Matsangas et al., 2014; Wright et al., 1995). These studies are reviewed in Sections 2.5 and 2.6 of this chapter.

Humans may take compensatory actions to minimise the effects of low-frequency, low-acceleration motion on manual task performance (for example Burton et al., 2011). These compensatory actions are taken to minimise motion induced body sway. To achieve an understanding on this issue, Section 2.7 provides a brief introduction to the major leg muscles involved in maintaining balance and depicts how an individual maintains balance during an upright stance. Finally, Section 2.8 reviews occupant comfort criteria that have been commonly used for assessing occupant comfort in wind-induced building motion environments.

2.2 Perception thresholds under low-frequency, low-acceleration motion conditions

Since the early 1970s, perception thresholds to low-frequency, low-acceleration motion have been investigated primarily using three methods: i) field studies and surveys of occupants conducted in buildings subjected to strong wind, ii) motion simulator experiments that determine perception thresholds in simulated building environments, and iii) field studies and surveys of occupants conducted in buildings subjected to artificially generated motion. This section reviews the literature on perception thresholds studies using these three methods.

2.2.1 Field studies and surveys of occupants conducted in buildings subjected to strong wind

The responses of occupants in buildings subjected to wind action provide the most realistic human responses to wind-induced building motion. It is an ideal situation for determining perception thresholds and other human responses for formulating criteria for assessing occupant comfort in a wind-induced building motion environment. Studies in buildings subjected to strong wind maintain the most realistic environment that may affect human responses to wind-induced building motion. This is an advantage that motion simulator studies can never mimic. However, it is difficult to instrument buildings to measure wind-induced building motion and to recruit participants in appropriate wind conditions. Furthermore, building owners and tenants are reluctant to participate in field studies because of commercial, legal, operational and security reasons. All these reasons make conducting field studies and surveys of human responses to wind-induced building motion difficult and uncommon.

Hansen et al. (1973) conducted the first field study that investigated the effects of wind-induced building motion on building occupants. They surveyed occupants of two approximately 40-storey tall office buildings in the United States, Buildings A and B, shortly after separate windstorms to investigate any relationships between perceptible motion and occupant discomfort. The windstorms induced perceptible motion during work days with durations of approximately five and six hours. The wind-induced motion of the buildings was measured, or estimated, using different methods. Prior to the onset of the windstorms, Hansen et al. (1973) had installed four accelerometers on the 34th floor of Building A to measure wind-induced motion. A maximum standard deviation acceleration of 2 milli-g was recorded for the storm peak over 20 minutes. For Building B, the building responses during the storm were deduced from an aeroelastic wind tunnel test. The maximum standard deviation accelerations averaged over a 20-minute storm peak were found to be five milli-g. As the standard deviation accelerations were determined by different methods, the standard deviation accelerations are not comparable. Furthermore, Hansen et al. (1973) did not define the standard deviation accelerations by error bars in the measurement and estimation exercise. A justification on the confidence level between the correlation between perception level and standard deviation acceleration is needed.

The survey results indicated that creaking sounds were the most reported cues for motion perception (average of Buildings A and B: 78.1%), followed by feelings of self-movement that included symptoms of motion sickness (average: 66.2%), movement of fixtures (average: 60.2%), looking outside of the building and sensing movement (average: 36.9%), and comments from co-workers (average: 27.3%). About 70% of occupants in Building A and 46.5% in Building B would object to the motion if it occurred once a day. The percentages dropped to 1.6% and 11.6% for Buildings A and B respectively if the motion occurred once a year.

Based on the objection rate, Hansen et al. (1973) established statistical relationships between return period and expected percentage of people objecting to the wind-induced building motion with root mean square (RMS) acceleration of 2 and 5 milli-g. After meeting with building owners, developers, and a structural engineer, Hansen et al. (1973) recommended that wind-induced building motion would be considered to be satisfactory if less than 2% of the occupants in the top one-third of the building objected to the motion. Based on the objection rate, Hansen et al. (1973) suggested that the 5 milli-g RMS motion would be considered satisfactory if it occurred with a return period of six years or more.

Hansen et al. (1973) presented a novel link between return period, motion level, duration of the peak of a storm, and objection rate to propose an acceptability criterion. Due to lack of information, the criterion was proposed for an acceleration magnitude then back calculated for the return period. Further, an objection rate of 2% of the occupants in the top one-third of the building was arbitrary. A slight variation in the objection rate would change the analysis result on the return period significantly.

Later, Goto (1983) interviewed occupants of five tall buildings located in the centre of Tokyo immediately after a strong typhoon in 1979. The heights of the buildings ranged from 170 to 210 meters above ground (43 to 55 storeys). Goto and his team distributed 1528 copies of a 29 questions survey about occupants' comfort issues. The response rate of the survey was 90.2 %.

Goto (1983) found that over 90 % of the respondents occupying the 13th floor or above perceived motion during the typhoon event. The percentage of respondent who visually sensed wind-induced building motion increased with an increase in floor level. However, no correlation was found between floor height and the percentage of respondents who sensed wind-induced building motion based on auditory cues or physical cues; 58.1% of respondents reported that wind-induced building motion slightly hindered their walking ability or performance of clerical work or light labour work; 72.3% of respondents reported they were affected physically or psychologically. Incidences of motion sickness, headache, anaemia, and stress increased as the floor height increased. Just over a third, 31.2% of respondents, took measures to deal with the physically or psychologically effects. However, Goto (1983) did not report the details of the measures. 36.1% of the respondents on or above the 30th floor would not tolerate the motion again or would only tolerate the motion once in 10 years. Contrary to the majority, a few people felt refreshed by the wind-induced building motion.

Results of this survey are valuable. Complementing the work by Hansen et al. (1973), Goto's (1983) field study indicated that wind-induced building motion could physically and/or psychologically affect building occupants. However, Goto (1983) did not directly measure the acceleration magnitude of the motion. Later, Goto (1983) installed accelerometers on a sixth building that was 60-storeys tall and measured the acceleration under the effects of a typhoon in 1982. Using the acceleration data, Goto (1983) estimated that the acceleration magnitudes of the five buildings due to the typhoon in 1979 that caused the occupant responses could have reached approximately 20 milli-g.

In a short communication, Lee (1983) reported occupants' responses to the motion of the Arts Tower (78-meter tall) at Sheffield University during a windstorm. Natural frequencies of the building in the east-west and north-south directions were 0.86 and 0.68 Hz respectively. During the peak of the storm, that lasted about four hours, Lee was presenting a lecture in a theatre situated on the 19th floor (72 meters above ground level) of the building for one hour. During the lecture, and in the coffee bar on the same level after the lecture, Lee and the students clearly perceived the building moving. They felt a swaying effect when they were either sitting or standing. Leaning against a wall with the back, shoulders and head in contact with the wall appeared to heighten the motion effect. However, no instances of sickness or nausea were reported. Further, Lee and the students did not consider the motion to be unnecessarily unpleasant.

Although Lee (1983) installed accelerometers to monitor the response of the building, the data-collection system was not in operation during the storm. In order to correlate the magnitude of the motion with the occupants' responses, Lee incorporated wind speed data measured at the top of the building into a series of wind tunnel tests to estimate the acceleration of the building during the storm. Results of the wind tunnel tests indicated that the peak accelerations along the east-west and north-south directions were 3.9 and 5.5 milli-g respectively, conforming to the perception thresholds published in literature (Hansen et al., 1973; Irwin, 1978). Lee concluded that the students were not concerned for their comfort and safety in the building during the windstorm.

Isyumov et al. (1988) observed acceleration of the Allied Bank Plaza building in Houston during Hurricane Alicia in August of 1983. This is the first reported record of the response of a major building subjected to winds of hurricane intensity. As shown in Figure 2.1, a peak acceleration of 43 milli-g at the top floor was recorded along one of the major stiffness axes vibrating at the fundamental frequency of 0.13 Hz, which is the lowest frequency at which resonance is said to occur. By reconstructing the wind field using all available meteorological information for the storm, Isyumov et al. (1988) estimated that the wind speed during the occurrence of the recorded peak acceleration of 43 milli-g may correspond to an event with a return period somewhat in excess of 50 years. This acceleration magnitude is far in excess of the recommended limits of all design guidelines pertaining to occupant comfort, for example “Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and offshore structures, to low-frequency horizontal motion (0.063 to 1.0 Hz), ISO 6897:1984” (International Organization for Standardization, 1984), which will be introduced later in Section 2.8 .

Further, Isyumov et al. (1988) quoted R.A. Halvorson, the individual who conducted the initial full-scale investigation,

“The motion was clearly perceptible and comparable to being on the deck of a very large ship. Some effort was required to balance oneself against lateral forces and walking required concentration.” (p.191)

The wind-induced building response, the high acceleration level and the long duration of the hurricane may also have created difficulties in performing manual tasks and/or provoked motion sickness in some building occupants. However, Isyumov et al. (1988) neither investigated the effects of the wind-induced building motion on performing manual tasks nor correlated the wind-induced building motion with incidence of motion sickness in building occupants. This may be because the occupants had left the building, highlighting the difficulty of studying the effects in buildings under strong wind events.

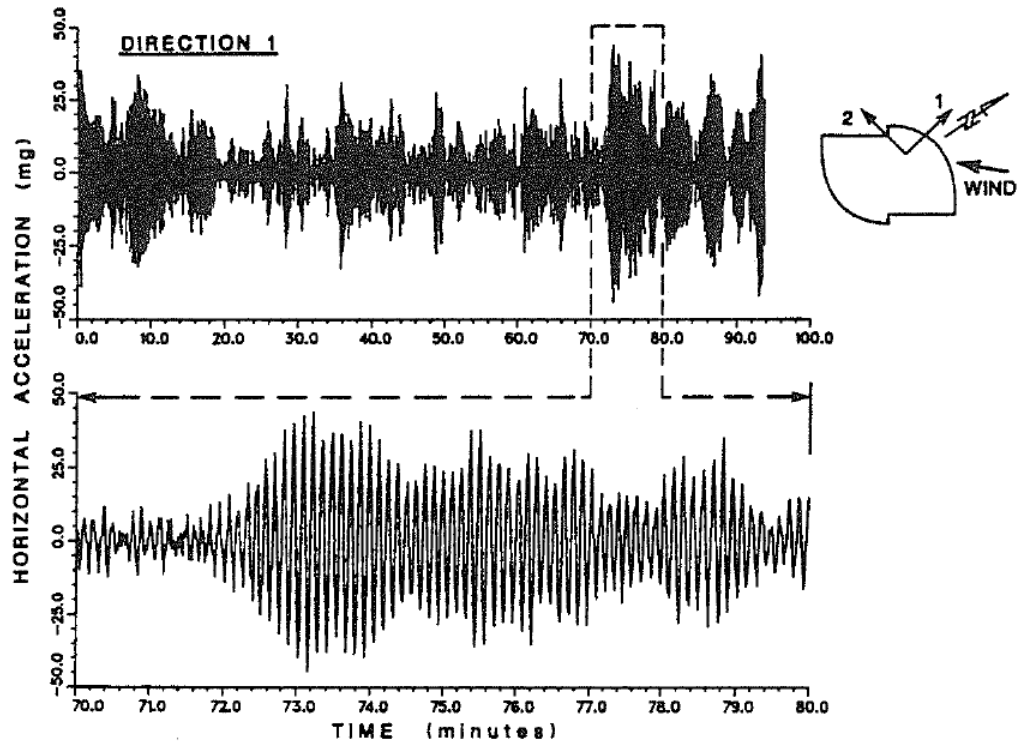


Figure 2.1. The highest peak acceleration of about 43 milli-g recorded at the top of the Allied Bank Plaza building in Houston during Hurricane Alicia in August of 1983 (reproduced from Isyumov et al., 1988).

Isyumov and Kilpatrick (1996) conducted a survey to obtain information on wind-induced motion of 27 tall buildings in the United States and Japan. The survey was intended for building owners, architects, and engineers who provided information and reports of motion perception, visual cues, audio cues, and complaints about discomfort or motion sickness. In most cases, Isyumov and Kilpatrick (1996) measured actual acceleration magnitudes of the wind-induced building motion that could be compared with the information of the survey and with recommended limits of acceptable motion, as proposed in Isyumov (1995).

Through this study, Isyumov and Kilpatrick (1996) made three observations. First, some of the extremely high accelerations were recorded in some buildings in Japan. These extremely high accelerations were likely due to the passage of a typhoon or a high wind event. However no motion report from occupants was received for those buildings. This may be because the buildings were unoccupied during typhoons or high wind events. Second, most measured building accelerations were relatively low and either comparative or less than the recommended limit of acceptable motion for office buildings. Finally, most reported building motion was accompanied with visual and/or audio cues. These results supported the argument that visual and/or audio cues drew attention to wind-induced motion and potentially degrade performance by heightening the overall sensation of motion. However, Isyumov and Kilpatrick (1996) did not report any evidence to demonstrate how the performance was degraded.

Isyumov and Kilpatrick (1996) also reconstructed the wind-induced acceleration of 47 other buildings at the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario and surveyed the building owners. Through comparing the acceleration and results of the survey, Isyumov and Kilpatrick (1996) concluded that the use of the criteria proposed in Isyumov (1995) appeared to solve building motion perception problems. However, Isyumov and Kilpatrick (1996) did not consider the effects of wind-induced building motion on manual task performance.

Denoon (2000) conducted a long-term survey investigating perception and tolerance of motion in three control towers in south-eastern Australia: Brisbane Airport Control Tower, Sydney Airport Control Tower and the Port Operations and Communications Centre in Sydney. Denoon (2000) simultaneously measured the wind-induced building response. The results demonstrated that the measured perception thresholds did not correlate well with previous sinusoidal research when compared using RMS acceleration. On the contrary, when compared using peak acceleration there was a strong correlation. It was concluded that the perception of full-scale building motion is driven by peak acceleration but not RMS acceleration. It was also concluded that the threshold of perception is frequency-dependent, corresponding to a lower perception threshold at higher frequency as shown in Table 2.1.

Table 2.1. Perception thresholds and motion frequencies determined from three control towers by Denoon (2000).

Tower	Frequency (Hz)	Perception thresholds, peak acceleration (milli-g)
Port Operations and Communications Centre in Sydney	0.39	2.8
Brisbane Airport Control Tower	0.54	2.5
Sydney Airport Control Tower	0.94	2.4

Since the participants involved in this study experienced motion frequently, Denoon (2000) suggested that the values of average perception threshold obtained in that study were likely to be lower than typically expected.

In accordance with the survey results, Denoon (2000) found that the magnitude of motion that leads to fear and alarm, and the frequency of occurrence of perceptible motion affected participants' tolerance of motion. A lack of correlation between participants who believed the building motion was unacceptable and participants who actually complained about building motion was also reported.

This research offers insights into the perception threshold of motion, and more importantly, into the tolerance threshold of motion. It was suggested that both education and habituation increase the tolerance of occupants to wind-induced building motion. One limitation of this research is the inability to control the motion environment, resulting in a lack of experimental results at other frequencies for establishing tolerance thresholds of motion in the lower frequency range that is more pertinent to modern tall buildings. Another limitation is that the participants of Denoon (2000) are trained professionals (air traffic controllers and port traffic controllers) who has got used to work in motion environment. Therefore, the participants of Denoon (2000) are not representative of building occupants such as office workers and home owners/residents.

2.2.1.1 Summary

In summary, a limited number of field studies have investigated occupants' perception thresholds to wind-induced building motion in buildings. While these studies provided the most realistic building environment for determining human responses to wind-induced building motion, they were unable to accurately establish relationship between human response with motion frequency and acceleration magnitude. This is mainly because building owners and tenants are reluctant to allow researchers measure responses of their buildings due to a combination of commercial, legal, operational and security reasons. Hence, installing equipment for measuring wind induced building motion is difficult. The majority of these studies retrospectively estimated acceleration magnitudes of the wind-induced building motion. This increases the level of uncertainty of the acceleration magnitude that induced those reported human responses in wind-excited buildings.

Although these field studies have focused on perception thresholds and/or tolerance of wind-induced building motion, some, for example Hansen et al. (1973) and Goto (1983), suggested that wind-induced building motion could have provoked motion sickness and affected occupants' manual task performance. However, studies on motion sickness/mild motion sickness, and occupant manual task performance in wind-induced building environment remain very limited.

2.2.2 Perception thresholds determined in buildings subjected to artificial excitations

Determining human responses in buildings subjected to artificial excitations can partially address some limitations of field studies or surveys of occupants in building subjected to strong wind conditions. Studies in buildings subjected to artificial excitations usually used vibration generators to excite the buildings. Using these, researchers therefore can accurately control acceleration magnitude, and to a lesser extent motion frequency. Researchers can also arrange participants for studies with great flexibility as they control the motion conditions. Further, studies in buildings subjected to artificial excitations maintain the environment that most realistically affects human responses. However, a limitation of studies in buildings subjected to artificial excitations is that they only produce sinusoidal building motion that differs greatly from random wind-induced building motion. Nevertheless, they provide the pathway for a fundamental understanding of human response to sustained motion at controlled acceleration magnitude and frequency.

Jeary et al. (1988) is one of the very few studies conducted in buildings subjected to artificial excitations. The study determined perception threshold of 24 participants using controlled motion in a 10-storey building and investigated the effects of motion on task performance (described later in Section 2.3). The natural frequency of the test building is approximately 1.6 Hz. The perception tests were carried out immediately after the task performance tests. Seated participants were tested on the ninth floor and acceleration magnitude was changed gradually to determine the perception thresholds.

Jeary et al. (1988) found that, at 1.6 Hz, the 50th percentile perception thresholds for seated test participants were 1.5 milli-g and 1.8 milli-g for lateral and fore-aft motion respectively. They further proposed that choosing an acceptable perception threshold should be based on the use of the building; for wind events with a 50-year return period, the perception thresholds should be chosen at the 2nd percentile for critical working areas, the 10th percentile for normal occupancy (offices and residential), and the 90th percentile for workshops.

A major drawback in using the results of Jeary et al. (1988) to design wind-sensitive buildings is that the results were determined at 1.6 Hz, which is well above the fundamental frequency of most wind-sensitive buildings.

Nakata et al. (1993) conducted a study in a building subjected to artificial excitations. This study was conducted at a frequency range from 1 to 6 Hz, to determine the perception thresholds of individuals in mid- and low-rise building environments. This study was an extension of the perception threshold study in a frequency range from 0.33 to 2.0 Hz conducted by a group of Japanese researchers using a motion simulator (for example Kanda et al., 1988).

The study was conducted in a test room constructed on the fifth floor of a seven story steel framed experimental tower. Fore-aft and lateral sinusoidal motion was generated using vibration generators installed on the sixth floor of the experimental tower. The motion was presented to the participants with increasing acceleration amplitude at five frequencies, 1.0, 1.9, 3.0, 4.0, and 6.0 Hz and perception of motion was indicated by pressing a button. Nakata et al. (1993) found that in the frequency range from 1.0 to 3.0 Hz, perception thresholds in the lateral direction were lower than the fore-aft direction whereas the perception threshold of fore-aft direction were lower than the lateral direction in the frequency range from 4 to 6 Hz. Nakata et al. (1993) also determined perception thresholds with perception probabilities of 2%, 10%, 50%, and 90%. The results showed that perception thresholds generally decreased as frequency increased from 1 Hz to 2 Hz, then increased as frequency increased from 2 Hz to 6 Hz. It should be noted that the perception thresholds determined in the frequency range from 1 to 6 Hz are more relevant to motion in mid- to low-rise buildings than wind-induced tall building motion.

2.2.3 Using motion simulators

Section 2.2.1 reported that conducting field studies or survey of occupants in buildings subjected to strong wind conditions is difficult because building owners and tenants are reluctant to provide access to buildings because of a combination of commercial, legal, operational and security reasons and it is hard to arrange test participants to occupy wind-sensitive buildings in an appropriate wind condition.

Using motion simulators to investigate human responses to motion can partially address the difficulties of conducting field studies or surveys in buildings subjected to strong wind conditions because of the controllability in motion frequency and acceleration and testing methods. In the early 1970s, engineers used motion simulators to determine perception thresholds of motion for the planning and design of wind-sensitive buildings due to a lack of knowledge and design guidelines on perception thresholds of motion.

Khan and Parmelee (1971) conducted one of the earliest studies that determined perception thresholds using a motion simulator. They aimed to develop a general approach and serviceability criteria for the design of any tall building, based on the results collected from an investigation which established design criteria for the 100-story (344 meters) John Hancock Centre in Chicago. Khan and Parmelee (1971) used a large circular platform with a diameter of 6.1 meters (20 feet), rotating at a constant angular velocity, to achieve a range of linear accelerations varying from 1 to 20 milli-g. Thirty test participants were asked to assess whether each tested acceleration magnitude was i) not perceptible, ii) barely perceptible, iii) perceptible, or iv) disturbing. The test participants were expected to experience motion during the simulator study that investigated effects on perception thresholds due to body postures (standing, sitting, and lying) and orientations relative to the motion directions (toward centre of the motion simulator, away from centre of the motion simulator, in direction of motion, and opposite to direction of motion).

Khan and Parmelee (1971) found that motion was perceptible at about 4 milli-g and that an acceleration magnitude of 20 milli-g was considered to be disturbing. Participants barely perceived motion at acceleration magnitudes between 4 to 7.5 milli-g and the position of the body did not greatly affect perception threshold of motion. However, Khan and Parmelee (1971) did not report nor discuss the motion frequency used in the experiment.

Chen and Robertson (1972) presented perception threshold results from two series of motion simulator studies (HATS-I and HATS-II) conducted in the mid-1960s. The studies were primarily to determine perception thresholds for the design and planning of the World Trade Centre towers in New York. Although HATS-I and HATS-II were very early investigations using motion simulators to explore perception thresholds of motion, these studies were tightly controlled and are still recognised as one of the most comprehensive studies on perception thresholds of motion. Chen and Robertson's (1972) results were also used to formulate acceleration criteria for assessment of occupant comfort (for example International Organization for Standardization, 1984).

In HATS-I, a motion simulator with dimensions of 2.7 x 4.9 meters (9 ft by 16 ft) was used. The motion simulator was mounted on a platform running on wheels, and could be moved simultaneously by hydraulic actuators in each of two orthogonal directions in the horizontal plane. The four factors studied included: i) period of oscillation (5, 10 or 15 seconds), ii) body orientation (fore and aft or side to side), iii) body movement (walking or standing), and iv) expectancy level (Level A: each participant was not aware of the motion characteristic of the simulator before testing; Level B: each participant was informed that the simulator would move and asked to tell the experimenter as soon as he felt motion; or Level C: each participant had experienced the motion of the simulator once and he was asked to repeat the test and to inform the experimenter as soon as he felt the room moving the second time.). A comprehensive full factorial experimental design was used to study the four factors. 72 participants were recruited and assigned to the 36 combinations of the four factors, each combination with two replications.

Chen and Robertson (1972) found that the effects of period of motion, body movement, and expectancy in influencing perception threshold were significant. The interaction effect between body movement and expectancy was also significant. In addition, they found that the perception threshold followed a log-normal distribution. Parameters of the log-normal distribution for perception thresholds were determined using the geometric means and the standard deviation calculated based on the data collected from the motion simulator experiments. These probability distributions illustrated the perception threshold corresponding to the percentile of test participants of each tested combination.

After completing the HATS-I study, Chen and Robertson (1972) conducted HATS-II to: i) confirm some of the HATS-I results; ii) validate the log-normal distribution assumption made for the perception thresholds; and iii) collect data from seated participants to assess the posture effects on the perception thresholds.

The motion simulator adopted in HATS-II had plan dimensions of 2.4 meters by 3.7 meters (8 by 12 ft) with a ceiling height of 2.6 meters (8 ft 9 in), smaller than the HATS-I motion simulator. The HATS-II motion simulator was suspended by four steel cables and guided by bicycle wheels mounted on two sides of the base of the simulator. An operator outside pushed the simulator to generate sinusoidal motion at an oscillating period of 10 seconds (a frequency of 0.1 Hz). Two factors, including body posture (standing or sitting) and expectancy level (Level B or Level C, both were the same as in HATS-I), were studied.

In the experiment, 40 participants were asked to stand or sit and to make aesthetic judgments about images presented in a slideshow. At the beginning of the experiment, each participant received a distraction and pre-condition and informed that the simulator was designed to move as the purpose of the experiment was to determine the perception threshold. The results indicated that body posture was the only statistically significant factor. Expectancy Levels B and C did not make any statistically significant difference on perception thresholds of the tested conditions, meaning that the prior motion experiences were not likely to play a significant role. The results also demonstrated the suitability of using the log-normal distribution to fit the perception threshold test data, in particular for participants tested in the standing posture. These probability distributions were likely to be beneficial for the performance based design approach. It should be noted that both HATS-I and HATS-II experiments omitted the effects of visual cues, which may significantly lower the perception threshold of motion, particularly for buildings vibrating in torsion. Furthermore, Chen and Robertson (1972) determined the perception thresholds, using sinusoidal motion, which were unrealistic in wind-excited tall buildings.

Realising that there was a lack of data for evaluating perception thresholds to yaw motion, Irwin (1981) conducted three series of motion simulator experiments; they investigated perception thresholds to pure yaw motion with and without visual cues and determined an equal sensation contour of a yaw motion. Ten participants were tested in the three series of motion simulator experiments.

The first experiment aimed to determine perception thresholds to sinusoidal pure yaw vibration without visual cues. Visual cues were avoided by covering the thick black window to prevent participants observing any light patterns from outside of the motion simulator, fixing an interior strip light to the ceiling, and restraining all cables and leads within the room from movement. Centre frequencies of the preferred one-third octave band ranging from 0.05 Hz to 3.15 Hz were chosen for the tests. The frequencies were presented in random order. During the experiment, one participant was tested at a time. The participant was seated with his/her spinal vertical axis coinciding with the central axis of rotation of the motion simulator. Acceleration was increased gradually. Participants were required to indicate when they start to perceive motion.

The second experiment aimed to determine perception thresholds to sinusoidal pure yaw vibration with visual cues. The experimental setup and procedures of the second experiment were the same as the first, except the blackout cover was removed from the window so that participants could see outside the motion simulator.

The third experiment aimed to determine an equal sensation contour to pure yaw motion with a reference RMS rotational acceleration magnitude of 0.065 rad/s^2 at 0.1 Hz. The experiment was conducted without visual cues. In this experiment, one participant was tested in each session. The participant was firstly exposed to the reference yaw motion for a period of 1 minute. The frequency of yaw motion was then changed to one of the preferred one-third octave band centre frequencies. Finally, the participant adjusted the acceleration magnitude of the yaw motion to match the feeling or sensation with reference to the yaw motion.

By considering the results of the three experiments, data from other field tests, and values from unpublished tests, Irwin (1981) proposed two satisfactory RMS yaw acceleration curves for the worst consecutive 10 minutes of a windstorm with return periods of at least 1 year and 5 years. Irwin (1981) also proposed one satisfactory RMS yaw acceleration curve for structures used solely by trained personnel who carry out skilled tasks in yaw motion of the worst consecutive 10 minutes of windstorms with a return period of 5 years, and a RMS yaw acceleration curve for safety issues.

Realising that translational and yaw motion often occur simultaneously, Irwin (1981) proposed Equation 2.1 below to assess the combined effects of translational and yaw motion on human responses. This method establishes a linkage between perception thresholds of translational motion and yaw motion.

Equation 2.1

$$\text{Combined magnitude} = h + r \times \theta$$

where

h is the vectorial summation of horizontal RMS acceleration orthogonal components at the frequency (f) and position under consideration (m/s^2)

θ is the RMS yaw acceleration (rad/s^2); and

$$r = \left| (1/f) - (0.57/\sqrt{f}) \right| + 0.2 \times (1 - 0.8/f)$$

Irwin and Goto (1984) extended the study presented in Irwin (1981) which investigated human perception values and equal sensation contours for pure yaw motion and proposed a method for assessment of the probable responses of occupants of fixed structures to combined yaw and translational motion. Irwin and Goto (1984) conduct a series of motion simulator tests to determine human perception thresholds and manual dexterity performance in laboratory conditions. These laboratory test results were compared with the value suggested in ISO 6897:1984 to validate the method used to combine the yaw and translational components developed earlier (Irwin, 1981). While this section summarises the experimental details and results of perception threshold tests, the experiment details and results of the manual dexterity performance tests will be summarised in Section 2.3 .

Two perception threshold tests were conducted: one for pure yaw motion (14 males and 6 females) and the other for combined yaw and lateral horizontal motion (17 males and 3 females). Frequency of test motion ranged from 0.01 Hz to 10 Hz. Both perception threshold tests were conducted in the absence of visual cues. In the perception threshold test using pure yaw motion, participants sat upright with the spine in contact with the chair-back. Further, the spine of the participant was in line with the axis of rotation of the room. In the perception threshold test that used combined yaw and lateral horizontal motion, participants sat with the spinal column at an eccentricity of 2.2 meters from the room axis of rotation. The experiment began with a gradual increase in acceleration amplitude. Until registering a perception of motion, the participant was invited to indicate the motion form and the approximate frequency of motion. Acceleration amplitude was then raised significantly and then gradually reduced until the participant was unable to perceive the motion.

Irwin and Goto (1984) found that the perception thresholds determined in the laboratory conditions agreed with the average threshold of perception as suggested by ISO 6897:1984. This validated the method used to combine yaw and translational motion (Irwin, 1981). Irwin and Goto (1984) further noted that noise and visual cues in practical structures tended to produce perception thresholds lower than laboratory conditions. This highlighted possible discrepancies between perception thresholds determined in laboratory conditions and in practical structures. Thus building design practitioners should use data collected in laboratory conditions with caution. Furthermore, Irwin and Goto (1984) discussed the effects of gender on perception threshold and reported that females tended to be slightly more sensitive to motion.

Between the late-1980s to mid-1990s, a group of Japanese researchers conducted comprehensive studies to investigate perception thresholds for a frequency range from 0.1 to 6 Hz (for example Kanda et al., 1988; Noguchi et al., 1993; Shioya and Kanda, 1993; Shioya et al., 1992). Results of these studies were then summarised in Tamura et al. (2006) and used to formulate guidelines for evaluation of habitability (Architectural Institute of Japan, 2004).

Kanda et al. (1988) used a spring pendulum motion simulator to investigate perception thresholds of low frequency motion. Uniaxial sinusoidal motion at frequencies of 0.33, 0.5, 0.8, 1.25 or 2 Hz was used in the study. The duration of each motion was six minutes, during which the acceleration amplitude was increased from 0.2 to 8 milli-g in 10 steps and then decreased from 8 to 0.2 milli-g, again in 10 steps; 119 participants were tested for the fore-aft and lateral orientations in a sitting posture. They were asked to switch on/off a pilot lamp when they felt the commencement or the cessation of motion. The effects of orientation, age and gender were examined.

Kanda et al. (1988) concluded that perception thresholds in the lateral direction were slightly lower than those in the fore-aft direction, whereas the stepping-down motion had slightly lower perception thresholds than the stepping-up motion. Females were more sensitive than male participants. Younger males were more sensitive than older males. However, Kanda et al. (1988) stated that all the above differences were minor in comparison with the variations amongst the individual data. Kanda et al. (1988) also proposed perception criteria for various percentiles (1st to 90th). Frequency dependence of motion perception over the tested frequency range was demonstrated. The 1st to 10th percentile lines were similar to those specified in ISO 6897:1984.

Goto et al. (1990) conducted a series of motion simulator experiments to determine perception threshold for a 50-storey steel building in Japan. The study used 0.23 Hz circular and elliptic motion at seven acceleration levels, ranging from approximately 1.35 to 15 milli-g. Goto et al. (1990) recruited only females to participate in the experiment because the authors believed that females are more sensitive to motion than males. Goto et al. (1990) also studied work efficiency, feelings of hindrance and uneasiness, difficulty of maintaining balance, swinging states of a hanging light, sloshing of bathtub water, and behaviour of small articles on a table. The following section only discusses the results of the perception threshold because this section only reviews literatures studying perception threshold.

Goto et al. (1990) found that perception thresholds determined under circular motion were slightly higher than elliptic motion. In general, at 0.23 Hz, 50% of the participants distinctly perceived motion at approximately 5 milli-g and all participants distinctly perceived motion at approximately 15 milli-g. It is important to note that Goto et al.'s (1990) results are of limited use as the experiments were conducted only at one frequency of 0.23 Hz. Furthermore, only females were recruited as participants. This may lead to bias results.

Shioya et al. (1992) examined the effects of different frequencies (0.125, 0.16, 0.2, 0.25 and 0.315 Hz), waveforms (uniaxial, elliptical and circular), and body orientations (lateral or fore-aft) on perception threshold of motion. A six degree-of-freedom motion simulator was used to produce the motion; 47 participants participated in the perception tests and were asked to classify each motion based on five perception levels, ranging from imperceptible to strongly perceptible, and to estimate the waveform of each motion. Shioya et al. (1992) found that participants were more sensitive to lateral motion. Further, the gradient of the regression lines determined for perception thresholds of uniaxial motion across the tested frequency was larger than the gradient for elliptical motion. About 50% of the participants could not distinguish between the uniaxial and elliptical motion. However, Shioya et al. (1992) did not offer an explanation for these observations. The researchers also fitted perception thresholds at each tested frequency with log-normal probability, and determined the corresponding threshold for the 2nd, 10th, 50th, and 90th percentile, illustrating that the 50th percentile regression lines of both uniaxial and elliptical motion coincided with the average threshold line of ISO 6897:1984.

Shioya and Kanda (1993) expanded the experiment reported in Shioya et al. (1992) using simulated random responses of a lightly damped, single degree-of-freedom system subjected to Gaussian white noise excitation. Apart from the motion waveform, the study used the same protocol as Shioya et al. (1992); 61 participants were tested in a sitting posture, in both fore-aft and lateral directions and were asked to push one of three buttons when they felt motion with the buttons representing imperceptible, barely perceptible and distinctly perceptible, respectively. Surprisingly, the results showed that the perceived accelerations were almost independent of the frequency in the range of interest (0.125 to 0.315 Hz), in contrast to the findings of the majority of previous motion perception studies. Shioya and Kanda fitted the perception threshold at each tested frequency with log-normal probability, and also determined the corresponding threshold for the 2nd, 10th, 50th, and 90th percentile. The results showed that the participants were generally more sensitive to lateral motion, consistent with the results determined in the previous study. The 50th percentile perception threshold of random motion, for both fore-aft and lateral directions, increased as frequency increased, whereas those of sinusoidal signals had the opposite trend. Although the results demonstrated that sinusoidal and random motion have different effects on the perception threshold, the authors did not identify the mechanisms that caused the opposite trends. Further research is needed to address the issue.

Noguchi et al. (1993) correlated psychological and physical responses of 20 female participants to motion by conducting a questionnaire survey and measuring the balance shift in a test room mounted on a six-degree-of-freedom motion simulator. The participants were subjected to linear, circular, elliptical, and figure-eight motion at frequencies of 0.1, 0.125, 0.167 and 0.2 Hz, and five acceleration amplitudes ranging from 4.8 to 14 milli-g. The duration of motion was 10 minutes. At the 5th and 10th minute after the commencement of each motion, participants ranked the motion in accordance with a scale ranging from imperceptible, slightly perceptible, clearly perceptible, fairly perceptible, to strongly perceptible. Participants also needed to rate the motion based on three complaint categories: discomfort, difficulty, and uneasiness using a five-point scale. By comparing the perception ranking obtained at the 5th and 10th minute, Noguchi et al. (1993) assessed that participants may habituate to the motion, resulting in a higher perceivable acceleration magnitude and lower ranking recorded at the 10th minute. In the measures of complaint, participants firstly felt discomfort, followed by feeling difficult, and finally felt uneasy to the motion.

In a series of motion simulator studies on manual task performance, Burton et al. (2011) determined perception threshold of participants to bi-directional, narrow-band random motion (as detailed in Section 2.3). Burton et al.'s experiments were carried out under 13 bi-directional, narrow-band random motion conditions, one no-motion start-up condition, and one no-motion control condition. The motion was described as narrow-band because the frequency components of the motion were focused near a single frequency. Among the 13 bi-directional, narrow-band random motion, 10 were reproduced at five peak acceleration magnitudes of 2, 4, 8, 16 and 30 milli-g at 0.25 and 0.5 Hz, and three were reproduced at three peak acceleration magnitudes of 2, 4, and 8 milli-g at 0.125 Hz. 14 participants indicated whether they had perceived any motion after the completion of each condition using a Boolean 'yes' or 'no' response. Burton et al. (2011) found that the relationship between cumulative percentage of individuals perceiving motion and acceleration for each frequency followed a log-normal distribution. Motion perception thresholds to bi-directional, narrow-band random motion are shown in Figure 2.2. Burton et al. (2011) concluded that the perception thresholds were consistent with other studies such as Chen and Robertson (1972).

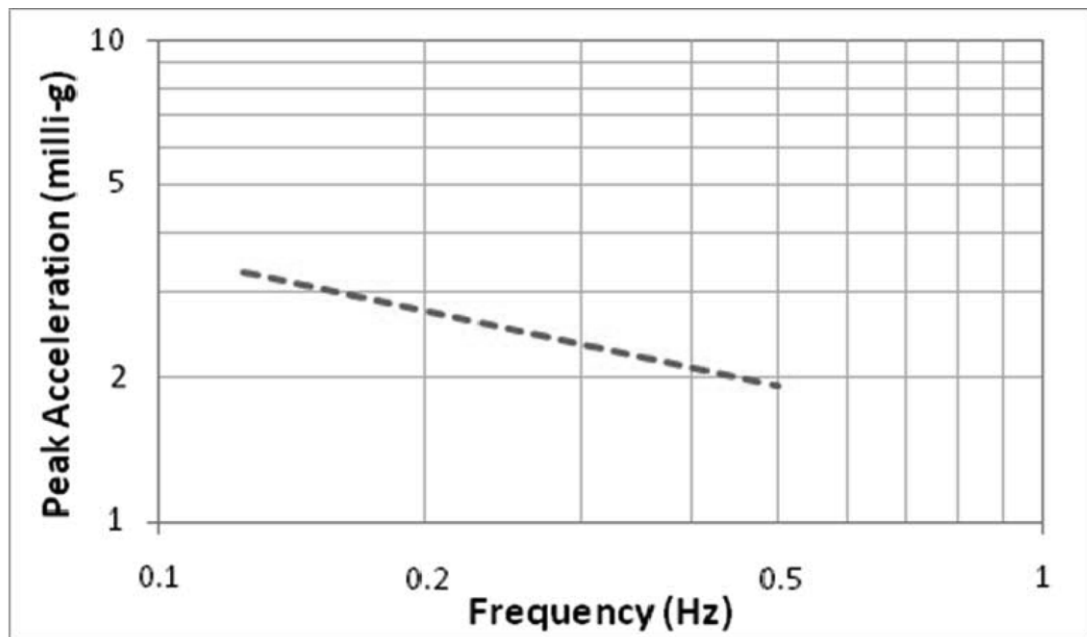


Figure 2.2. Motion perception thresholds (reproduced from Burton et al., 2011).

2.2.3.1 Summary

Over the last five decades, perception thresholds to motion have been extensively studied using motion simulators. Motion simulator studies, with their advantages of controllability in motion frequency and acceleration magnitudes, have determined perception thresholds to motion across a range of frequencies that are relevant to wind-induced building motion. Despite different measurement techniques, perception thresholds are similar across the motion simulator studies (Kwok et al. 2009). Results of these motion simulator studies suggest that perception thresholds generally decrease as frequency increases from 0.1 Hz to 1 Hz, confirming that perception to motion depends on motion frequency. Furthermore, the results from motion simulator studies indicate that perception thresholds of individuals are likely to follow log-normal distributions (for example Chen and Robertson, 1972; Tamura et al., 2006). This finding allowed researchers to use limited experimental results to determine the perception thresholds for various perception probabilities, hence formulating serviceability criteria/guidelines, for example, for the Architectural Institute of Japan (2004), that allows building owners and/or developers to use at their own discretion on building performance. Previous studies, such as Kanda et al. (1988) and Goto et al. (1990), indicated that female is more susceptible to building motion than male. However, no evidence was provided to explain the observations. Further research is needed to address the observations.

2.3 Manual task performance under low-frequency, low-acceleration motion conditions

While a majority of the studies on human responses to the effects of low-frequency, low-acceleration motion focused on perception thresholds and/or tolerance of wind-induced building motion, relatively little is known about how low-frequency, low-acceleration motion affects the performance of manual tasks.

In an survey on occupants of five tall buildings located in the centre of Tokyo immediately after a strong typhoon in 1979, Goto (1983) found that approximately 60% of respondents felt hindered while they were walking, attending clerical work or other manual tasks. This raised a concern that wind-induced building motion may adversely affect the manual task performance of building occupants. However, the reports were subjective with no quantitative measurement being carried out. Further, Goto (1983) did not provide details of the manual tasks performed by the respondents, nor discuss the mechanisms causing the hindrance.

Later, Irwin and Goto (1984) conducted four motion simulator experiments to investigate effects of motion on manual dexterity performance. They also validated the method proposed earlier by Irwin (1981) that used to combine the accelerations of yaw and translational motion, as shown in Equation 2.1 in Section 2.2.3 . Four manual dexterity tasks were used in Irwin and Goto (1984) to evaluate manual dexterity performance: i) threading three 300 mm lengths of 0.2 mm diameter thread through a 0.4 mm wide needle eye; ii) tracing over three 185 mm long vertical thin black lines using a red felt tip pen; iii) tracing over three squares orientated at 45°; and iv) tracing over a flower pattern.

The experiments were conducted under four types of motion with various combinations of yaw and translational motion. The motion direction, frequency range and number of participants used in the experiments are summarised in Table 2.2. For frequency range between 0.06 Hz and 1 Hz, the experiments were conducted at RMS acceleration magnitudes or combined acceleration magnitude suggested by curve 2 of Figure 1 of ISO 6897:1984, ranging from 49.8 milli-g (0.489 m/s^2) at 0.063 Hz to 15.9 milli-g (0.156 m/s^2) at 1 Hz. These acceleration magnitudes are the satisfactory RMS acceleration magnitudes suggested for off-shore fixed structures where non-routine or skilled manual operations are carried out under infrequently induced horizontal motion (International Organization for Standardization, 1984). For frequencies above 1 Hz, the experiments were conducted at RMS acceleration magnitudes or combined acceleration magnitude ranging from 15.9 milli-g (0.156 m/s^2) at 1.6 Hz and 2.5 Hz to 71.4 milli-g (0.7 m/s^2) at 10 Hz. These RMS acceleration magnitudes were chosen based on values suggested by the “Guide for the evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz), ISO 2631:1983” (International Organization for Standardization, 1983).

Table 2.2. Motion direction, frequency, and number of participants used in manual dexterity performance tests performed by Irwin and Goto (1984).

Experiment	Motion direction	Frequency	Number of participants
1	combined yaw and lateral motion	0.06 to 10 Hz	10 males and 1 female
2	combined yaw, fore-aft, and lateral motion	0.06 to 2.5 Hz	8 males and 2 females
3	combined yaw and fore-aft motion	0.06 to 2.5 Hz	5 males and 5 females
4	pure fore-aft motion	0.125 to 2.5 Hz	6 males and 6 females

From the results, Irwin and Goto (1984) found Equation 2.1 in Section 2.2.3 as proposed by Irwin (1981) was suitable to determine combined acceleration magnitudes of yaw and translational motion. Further, Irwin and Goto (1984) claimed that the RMS acceleration magnitudes suggested for off-shore fixed structures where non-routine or skilled manual operations were carried out under infrequently induced horizontal motion were generally satisfactory for performing the four manual dexterity tasks. This conclusion however is questionable because the performance on the tracing test could be degraded, on average, by more than 50% relative to the performance under static conditions as shown in Figure 2.3.

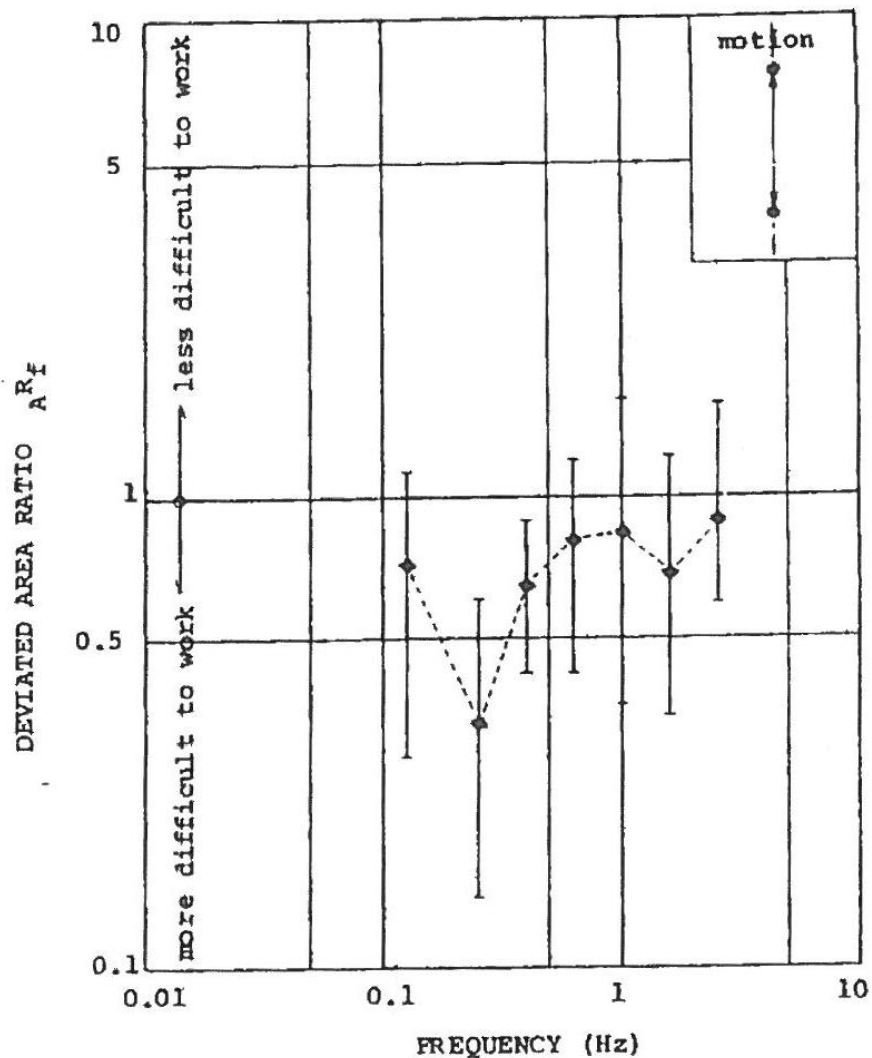


Figure 2.3. Performance of tracing tasks across frequency (reproduced from Figure 25 of Irwin and Goto, 1984).

Furthermore, the work reported by Irwin and Goto (1984) had three shortcomings. First, Irwin and Goto (1984) conducted the experiment at RMS acceleration magnitudes suggested for off-shore fixed structures. These RMS acceleration magnitudes, ranging from 49.8 milli-g (0.489 m/s^2) at 0.063 Hz to 15.9 milli-g (0.156 m/s^2) at 1 Hz, are higher than those that generally occur in wind-induced building motion. Therefore, the degraded manual dexterity tasks performance measured under the test conditions are not directly applicable to wind-induced motion of buildings used for general purposes. Furthermore, the experiments were conducted at one RMS acceleration magnitude for each frequency. Therefore, Irwin and Goto (1984) did not investigate effects of a range of acceleration magnitudes on performing manual dexterity tasks.

Second, some participants were able to satisfactorily perform the tasks even at peak acceleration magnitudes ranging from approximately 52 milli-g at 0.125 Hz to 22.4 milli-g at 1 Hz. It should be noted that these acceleration magnitudes are significantly higher than those proposed for buildings used for general purposes according to ISO 6897:1984. The satisfactory performance may be due to two reasons. First, the participants were all normally involved in work of a skilled nature such as workshop technicians well-trained for performing manual tasks. Therefore, the results may not be applicable for design, in terms of manual task performance, of buildings used by the general public. Second, these tasks may be too simple and not sensitive to effects of motion-induced body sway, motion sickness, and/or other subtle factors. Therefore, the participants could still perform satisfactorily under high acceleration magnitudes.

Finally, Irwin and Goto (1984) did not study the potential causes of performance degradation. This may be because Irwin and Goto (1984) suggested that participants were able to perform satisfactorily under high acceleration conditions. Therefore, there was no reason for them to investigate the potential causes of performance degradation.

Jeary et al. (1988) is one of the very few, if not the only, studies investigating task performance in a building environment subjected to artificial excitations. The main objective of the study was to ascertain whether task performance may be impaired in a controlled building motion environment. The experiment was conducted in a 10-storey Exeter Sixth Form College in the United Kingdom. The natural frequency of the test building is approximately 1.6 Hz. The controlled motion was generated using two vibration generators located on the tenth floor and 24 seated participants were tested on the ninth floor. Participants were tested in three test conditions: no motion and two low acceleration motion conditions with peak accelerations of either 1 milli-g or 4 milli-g. These peak acceleration magnitudes are generally well below perception thresholds as shown in previous studies (for example Chen and Robertson, 1972; Tamura et al., 2006), in particular 1 milli-g. Participants were tested under one test condition per day. Therefore they were tested for multiple days. Jeary et al. (1988) did not provide details of the tasks used in the study, but mentioned that one of the tasks was a proof reading task.

Jeary et al. (1988) found significant differences in proof reading performance between the tested conditions. However, the tested motion conditions did not impair performance of other tasks in general. Jeary et al. (1988) attributed the results to two potential reasons. First, the complexity of the tasks may have been too low so the participants were able to concentrate harder to compensate for motion effects. Second, the test duration may have been too short for any fatigue effects to show.

Although Jeary et al. (1988) found that effects of the imperceptible motion on task performance were not significant, the concept of the investigation was novel. A recent study has indicated that imperceptible motion can significantly affect a human's physiological behaviour (for example Hammam et al., 2014). Furthermore, Jeary et al. (1988) reported that seven of the 24 test participants claimed to experience motion sickness at the peak acceleration of 4 milli-g and two at the peak acceleration of 1 milli-g. Although the study on motion sickness was imprecise, Jeary et al. (1988) gave cues on effect of motion on motion sickness/sopite syndrome, and/or effects of motion sickness/ sopite syndrome on manual task performance in wind-induced building motion environment. A drawback of Jeary et al. (1988) is that the experiment was conducted at a frequency of 1.6 Hz, which is much higher than those of wind-induced building motion. Therefore, the results of Jeary et al. (1988) have limited applications to the majority of wind-sensitive buildings that usually have a fundamental frequency below 1 Hz.

Goto et al. (1990) conducted a series of motion simulator experiments to investigate perception thresholds and work efficiency/manual task performance due to motion. Results of perception thresholds, i.e. subjective responses, were summarised in Section 2.2.3 . Goto et al. (1990) quantified work efficiency/manual task performance by measuring the amount of spilt water during the process of pouring water into a bottle under motion conditions relative to static no motion conditions. Goto et al. (1990) found that manual task performance based on pouring of water depended on motion waveform. Participants performed worse under circular motion than under elliptical motion with the amount of spilt water measured under circular motion being greater than under elliptical motion. The manual task performance was largely unchanged at accelerations below 4 milli-g under circular motion condition at 0.23 Hz.

Goto et al. (1990) was possibly the first study that found simulated wind-induced building motion degraded manual task performance. However, the study was conducted at only one frequency - 0.23 Hz. Further investigations on manual task performance at other frequencies below 1 Hz are needed to collect more comprehensive information relevant to designs of wind-sensitive buildings. Second, Goto et al. (1990) only recruited females as participants. This may lead to biased results. Understanding the potential factors causing the observed degraded manual task performance is important. However, Goto et al. (1990) did not investigate this.

Burton et al. (2011) conducted a series of motion simulator experiments to evaluate manual task performance at frequencies that are typical for tall buildings. Bi-directional, narrow-band random motion, as shown in Figure 2.4, was used. Frequencies of the bi-directional, narrow-band random motion were 0.125, 0.25 and 0.5 Hz. Five peak accelerations at 2, 4, 8, 16, and 30 milli-g were used for 0.25 and 0.5 Hz motion. Due to displacement limitations of the motion simulator, Burton et al. (2011) only used 2, 4, and 8 milli-g at 0.125 Hz. The duration of each bi-directional, narrow-band random motion was 720 seconds.

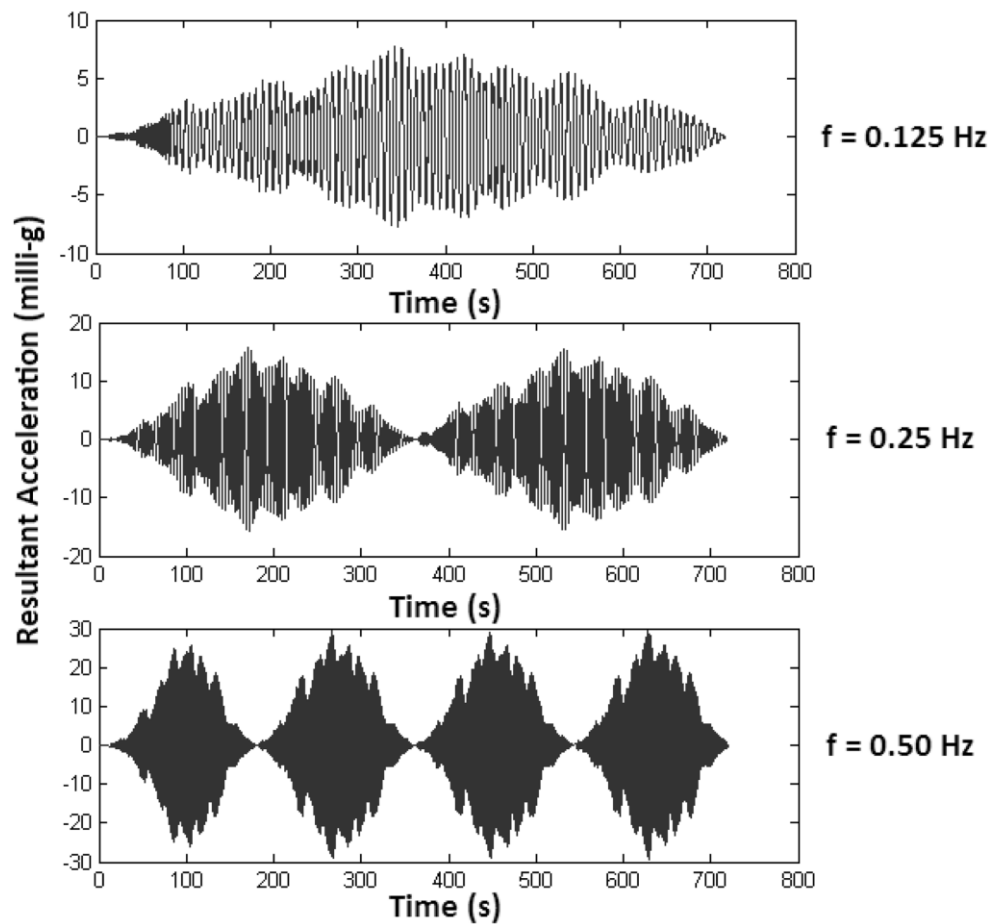


Figure 2.4. Examples of resultant acceleration time histories of bi-directional, narrow-band random motion (reproduced from Figure 2 of Burton et al., 2011).

Burton et al. (2011) used a first person shooter game to evaluate manual task performance. In the game, participants were required to shoot down obstacles along a set path. The overall completion time of the game depended on shot accuracy. The shot accuracy was also used to calculate the accuracy score. Participants performed the game under 13 motion conditions, one no-motion control condition and one no-motion start-up condition. The no-motion start-up condition was first presented to each participant, followed by a sequence that randomised the 13 motion conditions and the no-motion control condition.

Burton et al. (2011) found that the effects of bi-directional, narrow-band random motion on manual task performance in the form of a shooter game was not significant. The difference in overall completion time and accuracy scores measured under motion conditions and those measured under static condition were not significant. Furthermore, the manual task performance did not degrade or improve as a function of frequency or acceleration. Burton et al. (2011) suggested that higher acceleration magnitudes or longer exposure to motion might be required to induce performance degradation through either an increase in motion-induced body sway or exhaustion/fatigue in long duration events. Further, Burton et al. (2011) suggested that the young and fit participants recruited for the tests were able to “compensate for their difficulty in maintaining balance to overcome the potential degradation in performance” (p. 531).

Using a shooter game for evaluating manual task performance may contribute to the neutral conclusion that bi-directional, narrow-band random motion did not significantly affect manual task performance. First, the sizes of the targets and appearance time of targets were discrete. This reduced the resolution of shooting accuracy such that the bi-directional, narrow-band random motion did not influence the overall completion time and accuracy score. In fact, a manual task whose accuracy is quantified by using continuous quantities may increase the resolution of manual task performance/sensitive to motion effects. This is discussed later in Section 2.4 .

Second, the calculation of the accuracy score depended on a number of factors including the number of successful sequential shots, the positioning of the shot on the targets (head shots were awarded more points), and the time taken to complete the trial. These factors complicated the scoring system. The shooter game was a complex system of assessment such that the performance of participants may have been masked by other unquantified and uncontrolled human factors that overwhelm the sensitivity to motion effects. For example, successful prediction of the appearance of targets on a screen may enhance shooting accuracy and hence accuracy score of the game. Using a simple manual task that require minimum amount of skill can eliminate the effect of task difficulty. This is preferable for investigating effects of motion on manual task performance.

Interestingly, all participants in Burton et al. (2011) considered themselves as gamers who were likely to be familiar with playing TV games. Since the participants were skilled in playing TV games, they were not necessarily a representative sample of the general public. This may have also masked the effect of motion on the performance of the shooter game task. Furthermore, 13 males and one female were recruited in the study. Effects of gender were unbalanced. This may lead to bias results.

Using bi-directional, narrow-band random motion was novel and fits into the context of investigating the effects of wind-induced building motion on manual task performance. However, using bi-directional, narrow-band random motion may be a factor leading to the conclusion that motion did not significantly affect manual task performance. Manual task performance is highly associated with interruptions due to motion-induced body sway (Wertheim, 1998). The interruption is likely to be proportional to the inertial force acting on a human body, which in turn is proportional to acceleration magnitude. However, during narrow-band random motion the probability of occurrence of relatively high acceleration within the 720-second bi-directional, narrow-band random motion is relatively low. This suggests that a simultaneous occurrence of relatively high acceleration and appearance of a target in the shooter game is likely to be infrequent. During narrow-band random motion, participants might be performing the shooter game task at relatively low acceleration for a majority of time, hence resulting in an overall performance that was not significantly different from that measured under no-motion conditions.

Finally, Burton et al. (2011) thought that participants may have adequately compensated for the effects of motion by controlling their limbs, head, neck, and balance to minimise any effects on accuracy and completion time. This is a reasonable speculation but Burton et al. (2011) did not provide any supporting evidence.

2.3.1 Summary

Effects of low-frequency, low-acceleration motion on manual task performance are inconclusive. While Goto et al. (1990) quantitatively found that low-frequency, low-acceleration motion could degrade manual task performance, Burton et al. (2011), Irwin and Goto (1984), and Jeary et al. (1988) suggested that the effects of low-frequency, low-acceleration motion on manual task performance degradation are not significant. The inconclusive findings may be because of participant selection, the manual tasks tested, characteristics of motion, or a combination of these factors. For example, Goto et al. (1990), who measured performance degradation, only recruited females who are more sensitive to effects of motion. In contrast, Irwin and Goto (1984), who measured satisfactory performance, only used trained personnel for their experiments.

Performance degradation was measured during a continuous task, for example, pouring water into a bottle, as used in Goto et al. (1990) but not for discrete manual tasks, such as the shooter game used in Burton et al. (2011). All these factors or combinations of them make it difficult to conclude whether low-frequency, low-acceleration motion have any effects on manual task performance. Further, none of the studies established relationships between manual task performance, motion frequency and acceleration magnitudes, let alone determined potential causes that affect manual task performance.

2.4 Continuous tracking task performance under other types of motion conditions

Many studies have been conducted to measure manual task performance under conditions that simulate motion in transportation environments. Reviews on this topic can be found in the literature (for examples McLeod and Griffin, 1989; Wertheim, 1998). However, transportation environments usually have frequency and acceleration magnitudes much higher than those of wind-induced building motion. Furthermore, transportation environments usually involve vertical translational motion, pitch, and/or roll motion, which are significantly different from wind-induced building motion. Therefore, results of studies in transportation environments are not directly applicable to wind-induced building motion conditions. Nevertheless, the work in the field provides useful information to inform the experimental design of this research and/or provide insights into potential factors that may affect manual task performance in wind-induced building motion environments.

Goto et al. (1990) showed that low-frequency, low-acceleration motion could degrade performances of pouring water into a bottle, which is a kind of continuous task. However, Burton et al. (2011) found that performance of a shooter game, a kind of discrete task, under both static and motion conditions were similar. The difference suggests that the effects of low-frequency, low-acceleration motion are likely to be more significant on continuous than discrete manual tasks. Hence, a series of studies that investigated the effects of transportation motion on continuous tracking tasks are reviewed in this section.

McLeod and Griffin (1989) reviewed studies investigating the effects of vertical and/or horizontal translational motion on continuous control task (or continuous tracking task) performance. McLeod and Griffin (1989) defined a continuous tracking task as follow: *“Tracking tasks usually require that subjects continuously monitor a system (typically by observing a visual display) and perform a continuous sequence of controlling activities using the hands or feet. The object is to keep the state of the system within acceptable limits”* (McLeod and Griffin, 1989, p. 55).

In the review, McLeod and Griffin (1989) aimed to identify whether frequency, acceleration, direction of motion, characteristics of the control system and task, and the duration of exposure to motion could influence the effect of motion on the performance of continuous tracking tasks. McLeod and Griffin (1989) summarised that frequency, acceleration, and direction of motion interact to affect continuous tracking task performance. Further, the interaction effects are the single most important, and the most problematic effects on continuous tracking task performance. However, the studies reviewed by McLeod and Griffin (1989) generally used frequency (greater than 1 Hz) and RMS acceleration (greater than 50 milli-g) much higher than those occurring in wind-excited buildings. Furthermore, many of the studies were conducted under vertical motion that are not relevant to wind-induced building motion that occurs almost exclusively in the horizontal plane.

Studies investigating the effects of control systems and task characteristics on continuous tracking task performance have focused on the type of control devices, form of display, system dynamics, and/or the difficulty of the task performed. These studies have, generally, systematically compared a number of cases for a category. Therefore, the results were case specific. McLeod and Griffin (1989) proposed the effects of motion on continuous tracking task performance increased with the increase in task difficulty. However, the effects of task difficulty decreased when a task was already greatly affected by motion. This highlighted the importance of choosing an appropriate task for investigating the effects of motion on continuous tracking task performance.

McLeod and Griffin (1989) found the results of studies investigating effects of duration on tracking performance were inconclusive. No simple factors explained whether a task was sensitive to duration effects. Furthermore, McLeod and Griffin (1989) could not find a simple quantitative relationship between duration effects and tracking performance. They presented a behavioural model summarising the major physiological and psychological processes involved in tracking performance. These processes included visual processing, cognitive processing, and muscular actuation. The principal mechanisms likely to affect these processes included vibration breakthrough, visual impairment, neuro-muscular interference, and central effects. These principle mechanisms may, in turn, trigger secondary effects including increased workload, changes in strategy, and active compensation. This behavioural model systematically described the mechanisms affecting tracking performance. Hence it is useful for planning research to investigate effects of individual mechanism.

Earlier in 1988, McLeod and Griffin investigated whether vertical sinusoidal motion had any degradation on performance of a combined continuous and discrete pursuit tracking task and if yes, whether the degradation was frequency dependent. The experiments were conducted at frequencies ranging from 0.5 to 5.0 Hz and an RMS acceleration of approximately 200 milli-g (2.0 m/s^2).

A combined continuous and discrete pursuit tracking task was used. In the continuous pursuit tracking task, participants were required to use a device to control a cross on a display, keeping the cross inside the area of a moving target. The target was a 10 mm diameter circle moving randomly on the display. Participants' performance on the continuous pursuit tracking task was evaluated by the probability of the cross entering the target. The discrete pursuit tracking task was performed simultaneously with the continuous pursuit tracking task. The discrete pursuit tracking task required participants to press a button on the device whenever the cross entered the target. Furthermore, the participants needed to keep the button pressed as long as the cross was on the target and release the button when the cross was off the target. Participants' performance of the discrete pursuit tracking task was evaluated by the probabilities of pressing the button while the cross was on the target and while the cross was off the target.

McLeod and Griffin (1988) found the effects of vertical motion at frequencies ranging from 0.5 to 5.0 Hz were significant on the performances of the continuous pursuit tracking task. Performance degradation at 4.0 and 5.0 Hz was greater than at lower frequencies. Below 3.15 Hz, the performance of the continuous pursuit tracking task was independent of the frequency of vertical motion. McLeod and Griffin (1988) further discussed that the relative translational movement between participants' eyes and the display may be responsible for the degradation at 4.0 and 5.0 Hz while the degradation at frequencies below 3.15 Hz may be caused by central effects, such as distraction or anxiety, or some neuro-muscular mechanisms. The mechanisms causing the degradation under high and low frequency ranges were likely to be different. It is also noteworthy that the participants may have suffered central effects such as distraction and/or anxiety, which affected their task performance. Although McLeod and Griffin (1988) suspected that central effects degraded performance of the continuous pursuit tracking task at frequencies below 3.15 Hz, the study did not measure the severity of the effects nor correlate the severity of the effects and the performance degradation. McLeod and Griffin (1988) further concluded that degradation of the discrete pursuit tracking task appeared to be independent of frequency of the vertical motion. This highlighted that effects of motion on continuous tasks can be different from the effects on discrete tasks.

McLeod and Griffin (1993) studied effects of motion and exposure duration on performance of a continuous tracking task. The combined continuous and discrete pursuit tracking task used in this study was the same as the task used in McLeod and Griffin (1988). Therefore, a description is not repeated here.

In this second study, two independent groups of seven seated participants, 14 in total, performed a pursuit tracking task for 202.5 minutes on two separate sessions. One group was exposed to motion while the other group received no motion exposure. For the group exposed to motion, the participants performed the task under no-motion conditions for 11.25 minutes at the beginning, followed by 180 minutes exposure to vertical whole-body random motion, then under no-motion conditions for 11.25 minutes again at the end of a session. Fifteen seconds rest were allowed before the 180-minute exposure to the vertical motion. The vertical motion was a random motion that had a frequency bandwidth of one octave centred on 4 Hz. The acceleration time-history had an RMS magnitude of 1.46 m/s^2 and a crest (peak) factor of 4.13.

McLeod and Griffin (1993) divided the 202-minute session into eighteen 11.25-minute sub-sessions. Results of the 18 sub-sessions indicated that continuous tracking task performance declined as a function of duration. However, exposure to motion neither degraded the performance nor interacted with duration to degrade the performance. McLeod and Griffin (1988) suggested this might be because the motion magnitude used in the study was not high enough to cause measureable degradation for this combined continuous and discrete pursuit tracking task, although the test motion were much higher than those of wind-induced building motion. This is another example which shows that a task with a suitable level of difficulty and a high motion level are needed to obtain measurable degradation.

In another paper in the series of studies investigating effects of vertical and/or horizontal motion on continuous tracking task performance, McLeod and Griffin (1995) aimed to explore the mechanisms that caused manual task performance degradation. Eight male participants were tested in the study. The participants were required to perform tracking tasks under a no-motion condition and two vertical motion conditions at frequencies of 0.5 and 4.0 Hz, and both at RMS acceleration of approximately 215 milli-g (2.1 m/s^2).

Three tracking tasks were used, namely Tasks A, B, and C. Task A required participants to hold a control to keep a controlled element stationary in the centre of the display with no visual feedback; the display used in the experiment was switched off. In Task B, the display was switched on. Participants used a control to keep a controlled element stationary in the centre of the display with visual feedback. Task C was similar to Task B. In task C, a circular target, a controlled element, and a horizontal line were all shown on the display as clear visual references for keeping the controlled element on the circular target.

McLeod and Griffin (1995) found that, without a clear visual reference, a major mechanism causing degradation in Tasks A and B was a drifting of the controlled element on the display. The vertical motion may have increased muscle tension arising from either voluntary or involuntary responses to the motion. The result also suggested that the mechanism was independent of frequency between 0.5 and 4.0 Hz. Hence, the degradation mechanism was more likely to arise through a central effect rather than a biodynamic effect of the human body.

Participants in Task C had clear visual references. Using these clear visual references, participants were more easily able to detect and limit drifting of the controlled element in Task C. McLeod and Griffin (1995) suggested that the participants may have changed their strategy to perform Task C.

It should be noted that the mechanisms proposed in McLeod and Griffin (1995) were speculated mechanisms based only on results of analyses of the performances of Tasks A, B, and C. Additional direct measurements on central effect and/or muscle activity would have provided evidence to support the proposed mechanisms. Furthermore, only males were recruited as participants. This may lead to bias results due to gender effects.

2.4.1 Summary

While Goto et al. (1990) measured performance degradation under low-frequency, low-acceleration motion conditions using a continuous manual task, Burton et al. (2011) found effects of under low-frequency, low-acceleration motion were not significant on a discrete manual task. Effects of low-frequency, low-acceleration motion are likely to be more significant on continuous than discrete manual tasks. Hence, a series of studies that investigated the effects of transportation motion on continuous tracking tasks were reviewed. Although the studies were conducted under transportation motion conditions that are significantly different from wind-induced building motion, these studies are well-supported by evidence, hence the results provide useful insights into the effects of translational motion on continuous tracking task performance.

McLeod and Griffin (1988) showed that effects of vertical translational motion on continuous and discrete tracking tasks and the mechanisms causing degradations of continuous and discrete tracking tasks could be different. This confirmed that the shooter game, a kind of discrete tracking task, may have been a major factor that contributed to the neutral findings of Burton et al. (2011). Whereas degraded performance, as measured in Goto et al. (1990) by participants pouring water into a bottle, a kind of continuous manual task, may have contributed to their results.

A behavioural model was proposed by McLeod and Griffin (1989). The behavioural model suggested that tracking task performance was likely to be affected by vibration breakthrough, visual impairment, neuro-muscular interference, central effects, and secondary effects such as increased workload, changes in strategy, and active compensation. McLeod and Griffin (1988) found that 4.0 and 5.0 Hz vertical motion had greater degradation effects on continuous tracking task performance than at a lower frequency range between 0.5 Hz to 3.15 Hz. The performance degradations were likely due to different mechanisms. At 4.0 and 5.0 Hz, the degradations were likely due to relative translational movement between participants' eyes and the display used in the tracking task. On the other hand, the degradations at frequencies below 3.15 Hz may have been caused by a central mechanism, such as distraction or anxiety, or some neuro-muscular mechanisms. Since the frequency range, acceleration magnitudes, and motion direction of wind-induced building motion are significantly different from those of the vertical translational motion used by McLeod and Griffin (1988), mechanisms affecting manual task performance in wind-induced building motion conditions are likely to be different from those mechanisms causing task performance degradations under transportation motion conditions, as used by McLeod and Griffin (1988).

2.5 Incidence of motion sickness or mild motion sickness in low frequency, low acceleration conditions

Early field studies and surveys of occupants in buildings subjected to strong wind have focused on the effects of wind-induced building motion causing incidence of nausea, vomiting, and or other salient symptoms (for example Goto, 1983; Hansen et al., 1973). These symptoms in healthy occupants are usually provoked by prolonged exposure to relatively high acceleration building motion such as those occurring in infrequent extreme wind events. Hansen et al. (1973) reported that, on average, 41.3% of participants in two buildings felt motion sickness symptoms, including headaches, dizziness, queasiness, and nausea after an exposure for five to six hours to wind-induced building motion during windstorms. Goto (1983) reported that approximately 70% of respondents who felt motion were affected physically or psychologically, including motion sickness, headache, anaemia, and stress, after exposure for an extended period to wind-induced building motion. Lee (1983) however reported that, after approximately one hour exposure to wind-induced building motion, a class of students attending a lecture on the 19th floor (72 meters above ground level) of a 78-meter tall building reported no instance of sickness or nausea.

Incidence of motion sickness was also reported in motion simulator studies. In a perception threshold and manual task performance study, Irwin and Goto (1984) reported that participants were more prone to nausea and/or abdominal discomfort under motion conditions at frequencies below 1 Hz than under frequencies of above 1 Hz. Burton et al. (2005) studied effects of bi-directional, narrow-band random motion on the wellbeing of participants at frequencies ranging from 0.125 Hz to 0.5 Hz with peak factors of 1.7, 3.3, and 4.8, and peak accelerations ranging from 1 to 24 milli-g. Burton et al.'s (2005) results showed that 0.25 Hz and 0.5 Hz provoked the strongest reactions among the tested frequencies. At 0.25 and 0.5 Hz, approximately 50% of participants reported nausea at RMS acceleration magnitudes of 5 milli-g or above.

In addition to measurement of manual task performance, Burton et al. (2011) investigated effects of motion on nausea, tiredness, annoyance, disruption concentration, and maintaining balance. The study used bi-directional, narrow-band random motion at frequencies of 0.125, 0.25, and 0.5 Hz with peak acceleration ranging from 2 to 30 milli-g. By grouping the percentage of participants suffering the effects across all tested frequencies, Burton et al. (2011) found that the percentage of participants claiming to experience difficulty maintaining balance increased with acceleration. As shown in Figure 2.5, a similar trend across acceleration was also collectively found for the effects on nausea, tiredness, annoyance, and disruption concentration. As tiredness, annoyance, and disruption concentration are symptoms of motion sickness, these results suggested that bi-directional, narrow-band random motion are likely to induce symptoms of motion sickness. However, Burton et al. (2011) did not investigate the occurrences of nausea, tiredness, annoyance, and disruption concentration in detail, nor correlate the effects with manual task performance.

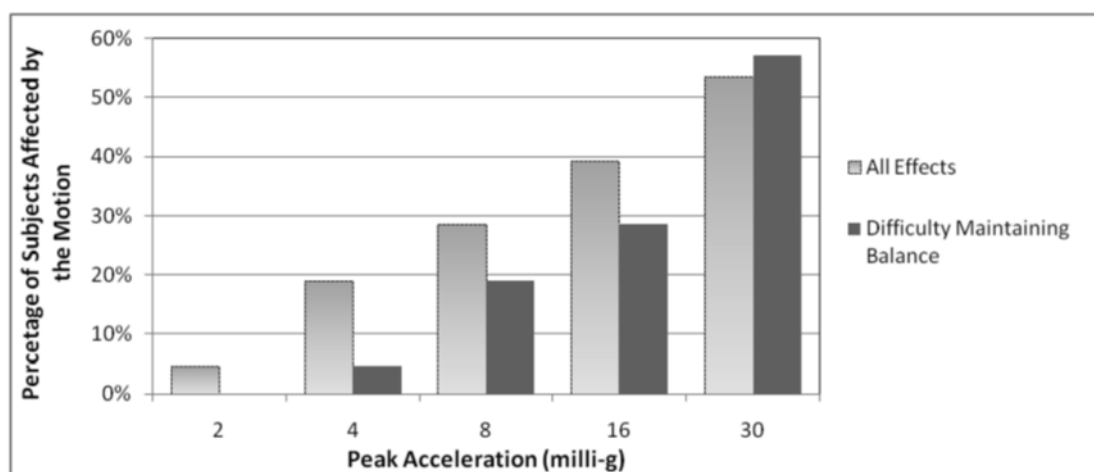


Figure 2.5. Percentage of participants affected by motion (reproduced from Figure 4 of Burton et al., 2011).

Walton et al. (2011) recently argued that, in wind-induced building motion environments, symptoms of sopite syndrome would occur more frequently than salient symptoms of motion sickness such as nausea and vomiting. Symptoms of sopite syndrome include a set of early onset symptoms of motion sickness such as, drowsiness, increased frequency of yawning, lack of motivation for physical or mental works, reluctance to participate in group activities, daydreaming, and low-level depression (Graybiel and Knepton, 1976; Matsangas and McCauley, 2014). These symptoms usually occur preceding, or in an absence of nausea or vomiting, during or after exposure to nauseogenic environments. Details of sopite syndrome will be discussed later in this chapter. A sophisticated experimental design is needed to detect symptoms of sopite syndrome because they are easily misattributed to the consequences of other daily activities. Walton et al. (2011) further proposed that a longitudinal survey and/or controlled motion simulator studies should be conducted to understand the full range of effects of wind-induced building motion on occupants such that buildings can be designed to maximise occupant comfort and performance.

Later, Lamb et al. (2013) conducted a survey to collect occupants' prior experiences of building motion, susceptibility to motion sickness, reported compensatory behaviours, and complaints about building motion. Lamb et al. (2013) distributed four thousand survey packs in Wellington, New Zealand and received 1014 responses. Wellington is one of the most consistently windy cities in the world due to the channelling effects of its mountain ranges on prevailing winds (Mathiesen, 2015). Furthermore, as Wellington is also prone to earthquake events the buildings tend to be more flexible than in other regions of New Zealand, making it a superior location for conducting a field study associated with wind-induced building motion. A majority of respondents were full-time workers. Among the respondents, 59% worked in 'professional' roles, 10.7% in 'management', and 14.6% in 'clerical/administration'. It is assumed that the employment nature of respondents was not related to manual tasks. The survey contained 95 items collecting information about respondents' current work environment and experiences with building motion. The survey also measured respondents' susceptibility to motion sickness and collected their demographic information.

Lamb et al. (2013) found that approximately 41% of respondents had felt wind-induced building motion. Among the respondents, 41.6% reported perceptible motion frequently, at least once a month. 41.9% reported they experienced difficulty in concentrating. This was the most frequently reported effect of building motion, suggesting that many building occupants have experienced motion sickness.

Respondents who were highly susceptible to motion sickness had a strong preference to avoid working on upper floors of buildings. However, the likelihoods for both high and low susceptible respondents to work on upper floors of buildings were similar. This increased the chance of exposing those highly susceptible respondents to wind-induced building motion hence increasing the incidence of motion sickness caused by wind-induced building motion for susceptible individuals.

Although a significant number (45%) of respondents informally complained about building motion to co-workers and/or family members, only 4.8% of respondents formally complained about the building motion to their team leader and 1.8% to the Chief Executive Officer (CEO) or a higher organisation level. Since building occupants in general almost never formally complain about building motion, Lamb et al. (2013) concluded that formal complaint is a poor indicator of the effects of building motion on occupants and practitioners should not heavily rely on formal complaint to formulate serviceability criteria to assess building performance.

Lamb et al. (2013) also found that 50% of the respondents who reported wind-induced building motion took compensatory actions to alleviate the effects of building motion. These compensatory actions include taking breaks outside their building and standing up and walking around. Lamb et al. (2013) further suggested that taking these compensatory actions were likely to reduce the work performance of the respondents as a secondary effect of building motion.

Other field studies most commonly surveyed participants' experiences of building motion caused by specific strong wind events (for example Goto, 1983; Hansen et al., 1973; Isyumov et al., 1988; Lee, 1983). These studies tried to correlate the occupant responses with frequency and acceleration of the wind-induced building motion either using direct acceleration measurements or retrospective estimate the acceleration using wind tunnel test techniques. However, Lamb et al. (2013) did not associate occupant responses with frequency and acceleration of wind-induced building motion. This may be because permission was not granted to Lamb et al. (2013) to measure and / or report accelerations of the buildings. As occupant responses may depend on frequency, it would have been beneficial if Lamb et al. (2013) had linked the extensive survey data with the frequency and acceleration of wind-induced building motion causing participants' unpleasant experiences. A majority of the respondents worked in 'professional', 'management', or 'clerical/administration' roles. The employment nature of respondents was not related to manual tasks. Therefore, the results of Lamb et al. (2013) cannot reflect the relationship between wind-induced building motion and manual task performance. Further research is needed to investigate the effects of wind-induced building motion on manual task performance.

Following the survey, Lamb et al. (2014) conducted a longitudinal field study to investigate the effects of wind-induced tall building motion on occupant wellbeing and work performance. The study surveyed the wellbeing and work performance of 100 participants in a range of wind conditions. The participants completed a total of 1909 short online surveys across eight months. The online surveys included 55 items requesting information about perception to building motion, health, subjective work performance, and their work environment. In addition Lamb et al. (2014) used a Stroop Test to evaluate objective cognitive task performance.

All 100 participants were office workers. Among the 100 participants, 47 were experimental participants working on high floors of 22 wind-sensitive buildings. The other participants were control participants working in near-ground floors. Since the control participants were unlikely to experience building motion under any wind conditions, results of these control participants were used to separate the wellbeing and subjective work performance of experimental participants under no motion baseline conditions from those under wind-induced building motion environments.

The wind conditions were categorised into high, medium, and low wind conditions using wind speed provided by the New Zealand National Institute of Water and Atmospheric Research climate database and corrected to a reference height of 150 meters in the Wellington central business district. Wind speed ranges and categories are summarised in Table 2.3.

Table 2.3. Wind speed ranges of the high, medium, and low wind conditions.

Wind condition	Wind speed
High	Strong breeze: > 18.5 m/s
Medium	Moderate breeze: between 9 – 18.4 m/s
Low	Calm breeze: between 0 – 8.9 m/s

Lamb et al. (2014) combined results of the health-related survey items to differentiate different levels of motion sickness. The results show that exposure to building motion significantly increased the incidence of motion sickness in building occupants. Rather than nausea, the symptoms of motion sickness mostly manifested as tiredness, low motivation, and/or distraction from work activities. These are also symptoms of sopite syndrome, a mild form of motion sickness (Graybiel and Knepton, 1976; Lawson and Mead, 1998; Matsangas and McCauley, 2014), discussed in further detail in Section 2.6 .

Lamb et al. (2014) found that subjective work performance significantly decreased as **symptoms** of motion sickness increased. The reduction in self-reported work performance was nearly one standard deviation (*SD*) below the self-reported work performance measured on calm days. Objective results of the Stroop Test were also consistent with this self-reported work performance. Further, those suffering from symptoms of sopite syndrome preferred to relocate their work location, took longer breaks (by 30 – 40%), and/or used painkillers to deal with the motion-induced discomfort. Although one third of the affected participants preferred to relocate their work location, no participant actually left their office because of the adverse effects of perceptible motion. This suggests that the affected participants adapted and/or tolerated the motion-induced adverse effects.

Lamb et al. (2014) was the first study to successfully measure sopite syndrome in wind-induced building motion environments. This is attributable to the sophisticated experimental design which measured the wellbeing and work performance of experimental and control participants across various wind conditions. This design ensured that symptoms of motion sickness and decrease in work performance were due to building motion not to other environmental issues. Further, as the surveys were completed near the end of business hours of each survey day, participants' responses about their wellbeing and work performance were fresh. By surveying the participants in such a timely manner, Lamb et al. (2014) were able to collect more reliable data than previous field studies that relied on retrospective surveys.

Lamb et al. (2014) successfully correlated sopite syndrome with subjective work performance and the objective performance of a cognitive task. This suggests that motion-induced sopite syndrome may have a measurable effect on manual task performance, making this worthy of further investigation. Further Lamb et al. (2014) did not associate occurrences of sopite syndrome with motion frequency and acceleration. Understanding these relationships will be beneficial in formulating guidelines for design habitable buildings subjected to wind excitations.

2.5.1 Summary

Detailed studies investigating the effects of wind-induced building motion on the incidence of motion sickness or sopite syndrome are very limited. A majority of previous studies suggested that wind-induced building motion may provoke salient symptoms of motion sickness, such as nausea and vomiting (for example Burton et al., 2005; Goto, 1983; Hansen et al., 1973). However, the presentation of salient symptoms of motion sickness is likely to occur at high acceleration magnitudes that are more relevant to extreme windstorms. Recent studies show that wind-induced building motion at low acceleration magnitudes, which occur more frequently than extreme windstorms, may provoke sopite syndrome (a mild form of motion sickness) for a significant number of building occupants, particularly those prone to motion sickness (Lamb et al., 2013, 2014; Walton et al., 2011). Lamb et al. (2014) established a relationship between severity of sopite syndrome and subjective work performance and cognitive performance. This suggests that sopite syndrome may have a measurable effect on manual task performance, making this worthy of further investigation to advance our understanding of human responses to wind-induced building motion. Furthermore, Lamb et al. (2014) found that, in Wellington, days with wind speed higher than 18 m/s would probably cause sopite syndrome in 5.4% of occupants. Lamb and Kwok (2016) later reported that approximately 50 days in a year would have wind speed that is likely to cause sopite syndrome in building occupants. This occurrence frequency of sopite syndrome may cause multi-million US dollar economic losses. It is noteworthy that the results of Lamb et al. (2014) were derived from data collected from an approximately eight-month long longitudinal study. A longer study duration will increase the reliability of the results. To date, no study has been conducted to investigate the occurrence frequency of sopite syndrome of other less windy city. Further studies and/ or analyses are needed to address the prevalence and potential impact of sopite syndrome on building occupants, particularly in windy cities with wind-sensitive tall buildings.

2.6 Sopite syndrome

Extensive studies have been conducted to investigate motion sickness and its signs and symptoms, individual susceptibility, situations that are provocative to motion sickness, mechanisms eliciting motion sickness, theories of motion sickness, and how to avoid or attenuate motion sickness (for example Golding, 2006; Lackner, 2014; Money, 1970; Reason and Brand, 1975). It is well known that nausea, vomiting, cold-sweating, and pallor are major salient signs or symptoms of motion sickness. Other early onset or mild symptoms of motion sickness, such as drowsiness, lethargy, decreased ability in concentrate, disinterest and disinclination to physical and/or mental work, and lack of participation in group activities may be unrecognised or misattributed to the demand of other daily activities. Graybiel and Knepton (1976) defined these early onset or mild symptoms of motion sickness as sopite syndrome. Since sopite syndrome is likely to be the most important factor in wind-excited buildings (Lamb et al., 2014; Walton et al., 2011), the review hereunder focuses on studies on sopite syndrome.

Graybiel and Knepton (1976) were the first to use the term “sopite syndrome” to collectively describe the early onset or mild symptoms of motion sickness centred around drowsiness. In studies using Slow Rotation Room (SRR), Graybiel and Knepton (1976) found that sopite syndrome can be the main or sole manifestation of motion sickness under two circumstances. First, when the characteristics of motion stimuli are matched to a person’s susceptibility, sopite syndrome can be evoked either before other symptoms of motion sickness appear or in their absence. Second, it can persist when salient symptoms of motion sickness disappear due to individuals adapting to the prolonged exposure in a motion environment.

Wright et al. (1995) aimed to determine the incidence and effects of nausea and sopite syndrome among medical transport personnel. They also investigated the effects of nausea and sopite syndrome on attention and concentration performance; 26 medical transport personnel participated in this study and they needed to travel via helicopters and/or ambulances when they were on duty. They completed a questionnaire to assess their susceptibility to motion sickness upon beginning the study.

An additional questionnaire evaluated each individual for symptoms of nausea and sopite syndrome during transport, as shown Figure 2.6. The participants were classified as experiencing nausea syndrome if either nausea or vomiting, or two or more of the minor symptoms, appeared during transport, and/or experiencing sopite syndrome if two or more of its six symptoms appeared.

Nausea Syndrome^a	Sopite Syndrome^b
Major symptoms	Drowsiness
Nausea	Malaise
Vomiting	Yawning
Minor symptoms	Headache
Warmth/flushing	Disinclination for work
Dizziness	Lack of participation in group activities
Diaphoresis	
Pallor	
Salivation	
Stomach awareness	
Stomach discomfort	

^aFrom Miller and Graybiel (7).
^bFrom Graybiel and Knepton (5).

Figure 2.6. A questionnaire used to evaluate each individual for symptoms of nausea and sopite syndrome during transport (reproduced from Table 1 of Wright et al., 1995).

Wright et al. (1995) also evaluated the effects of nausea and sopite syndrome and the effect of transport on attention and concentration performance using a Digit Span Test (DST). During DST, participants were given a series of numbers to memorise and repeat forward. If the participants could accurately repeat this series of numbers, the number of digit of the next series of number increased by one. This procedure was repeated until the participant made an error. The participants were then given a series of numbers to repeat backwards in a similarly progressive manner. Participants performed the DST at the completion of an air or ground transport. They also performed DST, as a control evaluation, during a shift in which a transport was not performed.

Wright et al. (1995) found that 46% and 65% of the participants experienced symptoms of nausea and sopite syndrome respectively. 23% experienced neither symptoms of nausea nor sopite syndrome. Digital span test performances of the 20 participants who were measured after transportation were worse than the control condition, that is, no transportation condition. For those who experienced nausea and/or sopite syndrome, their DST performance, measured after transportation, was also worse than those in the control condition. Wright et al. concluded that nausea and/or sopite syndrome significantly degraded attention and concentration performance.

Later, Lawson and Mead (1998) conducted a review on sopite syndrome. They suggested the effects of sopite syndrome may be “particularly hazardous in transportation settings” (p. 181) because practitioners in that environment may have been subjected to other performance challenges such as sleep deprivation. Interactions between sopite syndrome and illnesses such as sleep disorders or depression may have further confused diagnosis.

Matsangas and McCauley (2014) have identified three concerns about the definition of sopite syndrome originally given by Graybiel and Knepton (1976). The three concerns are non-specificity of soporific symptoms, the health state of the individuals, and the existence of a motion stimulus. Ignoring the health state of the individuals and the existence of a motion stimulus actually lead to the non-specificity of soporific symptoms. This is because the symptoms are not uniquely provoked by nauseogenic stimuli but can also be provoked due to stress, illness, or other reasons. To address these concerns, Matsangas and McCauley (2014) re-defined sopite syndrome as: “Sopite syndrome is a symptom complex that develops as a result of exposure to real or apparent motion and is characterised by excessive drowsiness, lassitude, lethargy, mild depression, and reduced ability to focus on an assigned task. Sopite syndrome is most clearly distinguished in a healthy individual free from pathological conditions that engender similar symptoms and not suffering from sleep deprivation, mental or physical fatigue, or increased levels of physical activity” (p. 673).

Recently, Matsangas et al. (2014) investigated effects of mild motion sickness and sopite syndrome on multi-tasking cognitive performance; 51 relatively young military offices (45 males and six females; age, mean = 35.4 years, standard deviation = 5.74) performed four components of SYNWIN™ (Activity Research, Inc.) to assess multi-tasking cognitive performance. The four components included a memory search task, an arithmetic problem task, a visual reaction task, and an auditory reaction task. These cognitive tasks required skills commonly found in various work environments and occupations. The experiments were conducted under 0.167 Hz sinusoidal motion that comprised heave, roll, and pitch components. The participants were divided into three groups and all of them were exposed to two experimental sessions each lasting one hour and consisting of six 10-minute blocks. Two groups received motion only in the first or second session (motion – no motion group or no motion – motion group), whereas the control group did not receive motion in both sessions (no motion – no motion group). Motion sickness susceptibility was evaluated using a revised version of the Motion Sickness Susceptibility Questionnaire (Golding, 1998). The severity of motion sickness symptoms and soporific severity were assessed at the end of each 10-minute block using the Motion Sickness Assessment Questionnaire (MSAQ) and the Stanford Sleepiness Scale (SSS) respectively. Participants were classified as symptomatic if the symptom severity in motion was greater than in the static condition. On the other hand, participants were classified as asymptomatic if they did not experience any symptoms in both static and motion conditions.

Matsangas et al. (2014) found that motion sickness and sopite syndrome had significant adverse effects on composite, memory, and arithmetic task scores during the second session. This highlighted the order effects on cognitive task performance under motion conditions. Matsangas et al. (2014) proposed a conceptual model to describe the evolution of cognitive performance over time for asymptomatic and symptomatic participants in the 1st and 2nd experimental session, as shown in Figure 2.7. At the beginning of the experiment, participants improved their cognitive performance through learning, reaching a plateau over time. The cognitive performance of asymptomatic participants was maintained even when 0.167 Hz motion was introduced. The introduction of 0.167 Hz motion however further complicated the cognitive performance of symptomatic participants between the 1st and 2nd experimental session. Apparently symptomatic participants who experienced sopite syndrome were able to overcome its effects in the first session by focusing more on the task when it was still novel and interesting, but were unable to maintain the same level of vigilance in the second session, probably because they were familiar with it or had lost interest in the task.

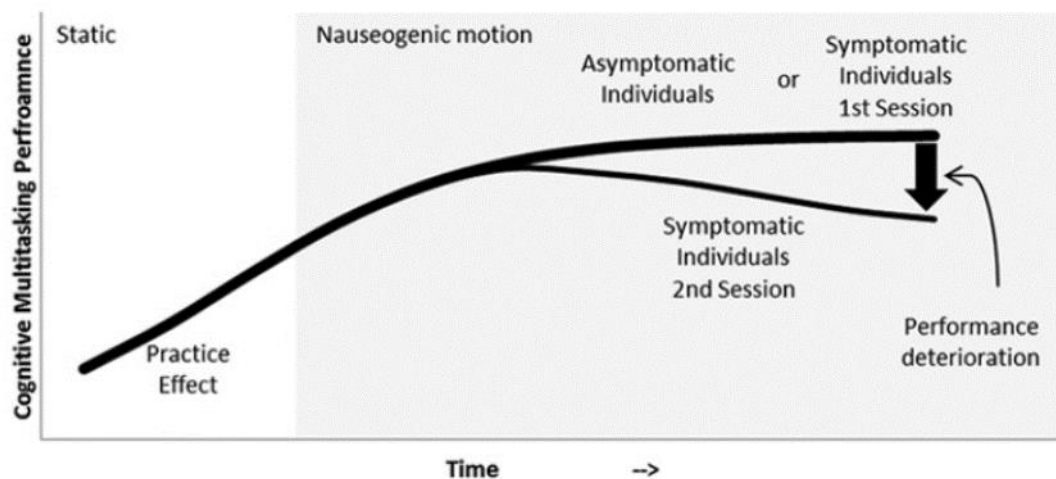


Figure 2.7. A conceptual model describing the evolution of cognitive performance over time for asymptomatic and symptomatic participants in the 1st and 2nd experimental session (reproduced from Figure 4 of Matsangas et al., 2014).

By considering motion sickness or sopite syndrome as a stressor, Matsangas et al. (2014) postulated that the effects of experimental sessions on the relationship between symptomatology and cognitive performance may be related to the capacity of attentional resources and their investment in performing the cognitive performance. Experiencing motion sickness or sopite syndrome may have occupied part of the attentional resources, potentially forcing symptomatic participants to perform the cognitive tasks at the overloaded or near-overloaded zone.

These stressor-based models may also be applied to degradation, if any, of manual task performance. As noted earlier in the summary of McLeod and Griffin (1989), performing a tracking task involves a visual processing stage, a cognitive processing stage, and a muscular actuation stage. Experiencing motion sickness or sopite syndrome may occupy attentional resources that are originally used in any one of the three stages of the tracking performance.

2.6.1 Summary

Since 1976, sopite syndrome has been used to collectively describe the symptoms which appear at the early onset of motion sickness or mild motion sickness centred around drowsiness (Graybiel and Knepton, 1976). Effects of sopite syndrome have been investigated in transportation motion environments (for example Matsangas et al., 2014; Wright et al., 1995). These effects may be “particularly hazardous in transportation settings” (Lawson and Mead, 1998, p. 181) because, in addition to sopite syndrome, practitioners in a transportation environment may have been subjected to other performance challenges such as sleep deprivation. Further, interactions between sopite syndrome and illnesses such as sleep disorders or depression may further confuse diagnosis (Lawson and Mead, 1998). While some studies have found that sopite syndrome can degrade cognitive task performance in transportation motion environments (for example Matsangas et al., 2014; Wright et al., 1995), no study has investigated the effects of sopite syndrome on manual task performance, let alone its effects on the performance of a manual task under wind-induced building motion conditions.

2.7 Postural control of standing human

Previous studies have shown that building occupants took various kinds of compensatory actions to relieve effects of wind-induced building motion. Goto (1983) reported that 32% of respondents who were physically or psychologically influenced by wind-induced building motion took measures to relieve the effects. Although Goto (1983) noted that no one relieved the effects by lying down or taking medicine, the author did not give any details of other compensatory actions taken by the affected respondents. A piece of anecdotal information suggested that occupants of a building that exhibited perceptible wind-induced motion several times per year preferred to eat out on windy occasions, apparently as a mean of avoidance (Melbourne and Cheung, 1988). Lamb et al. (2013) reported that 50% of respondents who felt wind-induced building motion attempted to take breaks outside their buildings and stand up and walk around to alleviate the effects of motion. Lamb et al. (2013) also noted that some occupants attempted to self-medicate with analgesic and motion sickness tablets in wind-induced building motion environments. In a longitudinal study, Lamb et al. (2014) reported that, under wind-induced building motion conditions, participants suffering more severe symptoms of motion sickness on average spent 67 minutes outside the building, which is significantly longer (or 46% longer) than those who reported no symptoms (46 minutes). One participant even used motion sickness tablets when the wind-induced building motion was barely perceptible.

In a motion simulator study, Burton et al. (2005) reported that approximately 40% of participants who experienced nausea at 0.25 Hz and 0.5 Hz left the motion simulator during the course of the experiment. This suggests that participants in laboratory experiments take some form of compensatory actions to alleviate the adverse effects of motion. In another motion simulator study, Burton et al. (2011) suggested that young and fit participants were able to effectively compensate for the difficulty in maintaining balance caused by bi-direction narrow-band random motion such that the motion did not cause degradation in the manual task performance.

It can be seen that building occupants may take various actions to compensate the effects of wind-induced building motion. Some of these measures are directly related to an increase in muscular effort to reduce body sway to maintain postural stability (Wertheim, 1998). Hence, understanding how an individual maintains balance in an upright stance will provide insights on how muscular effort may be increased to compensate for the effects of motion and the influence of body sway on manual task performance under wind-induced building motion conditions. A brief introduction is given hereunder to introduce the major leg muscles involved in maintaining balance and to show how an individual maintains balance in an upright stance.

2.7.1 Maintaining an upright posture

An individual uses the central nervous system (CNS) to integrate sensory information from multiple sources, such as somatosensory, visual, and vestibular systems, and subsequently generates corrective torque about the ankle joint to maintain a stable, upright posture (Day et al., 2013). The generation of a corrective torque about the ankle joint depends on activating the lower leg muscles to act on the ankle.

Soleus (SOL) and tibialis anterior (TA) are two major leg muscles at the ankles that are involved in maintaining a stable upright standing posture. Soleus (SOL), as shown in Figure 2.8, is a powerful plantarflexor running from just below the knee to the heel. It functions to maintain an upright standing position by continuous activation when an individual stands freely, in which the centre of gravity is slightly forward; this prevents the body from falling forward if perturbed (Fitzpatrick et al., 1992). SOL has a higher proportion of slow muscle fibres thus it can provide prolonged continuous contraction for maintaining balance and/or correcting postural sway.

TA is the largest ankle dorsiflexor. It can be seen superficially in the front of the lower leg. It is responsible for flexing the ankle upward and inverting the foot. Under quiet standing or small perturbation that is insufficient to jeopardize balance, the TA usually remains silent (Fitzpatrick et al., 1992). The CNS however activates the TA when perturbation is sufficiently large to challenge balance. Activation of the TA primarily aims to prevent the body from falling backward.

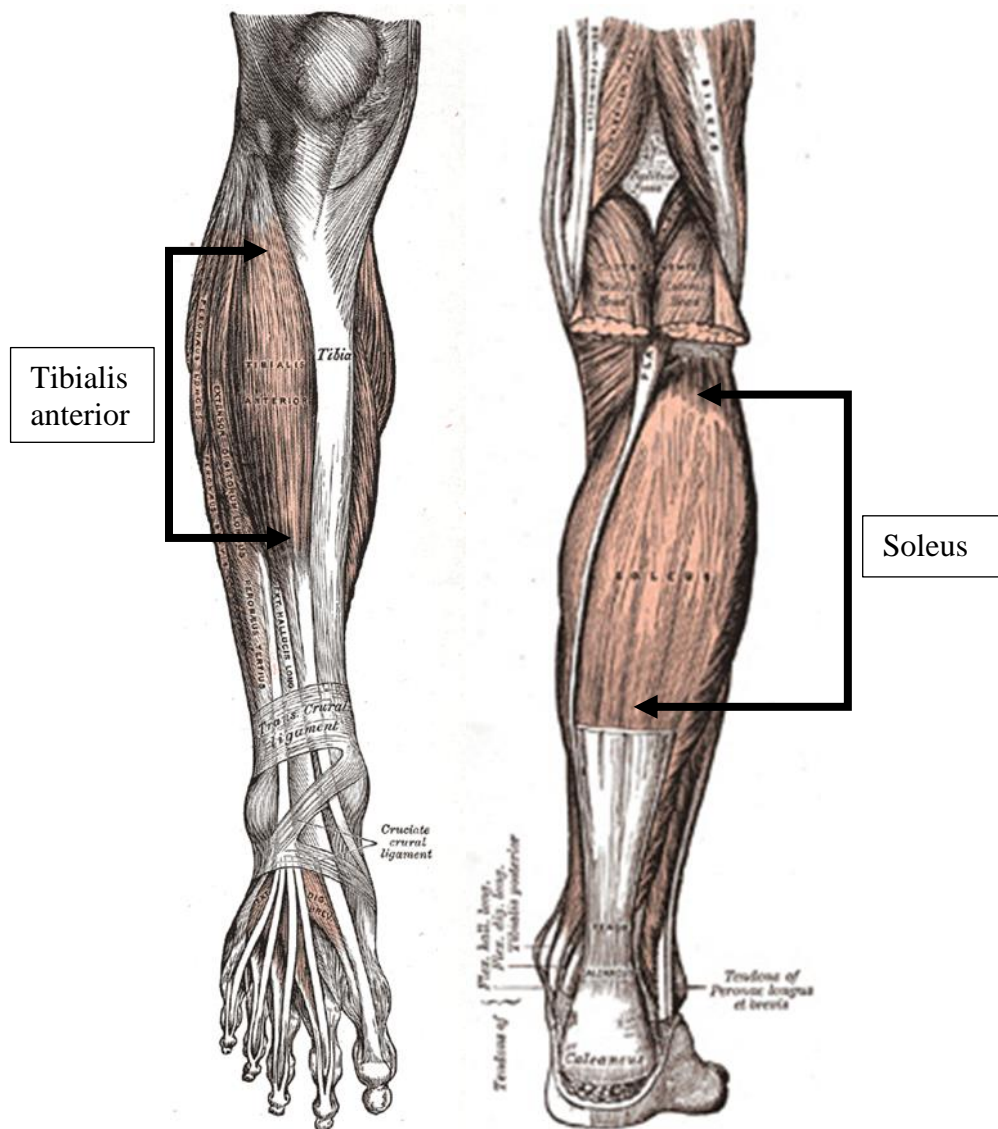


Figure 2.8. (Left) Tibialis anterior muscle and surrounding structures. This is a view of the front of the right leg (reproduced from Gray, 1918). (Right) Soleus muscle and surrounding structures. This is a view of the back of the right leg; most of the gastrocnemius muscle has been removed (reproduced from Gray, 1918).

Winter (1995) has detailed how an individual adjusts the activation of leg muscles to produce corrective torque about the ankle for maintaining balance under bipedal quiet standing. Figure 2.9, reproduced from Winter (1995, p. 195), shows variations of distance between the centre of gravity (COG) of the body and the ankle (g), distance between centre of pressure (COP) locations and the ankle (p), angular accelerations (α), and angular velocity (ω) of an individual swaying back and forth in a quiet bipedal standing posture at five different points in time.

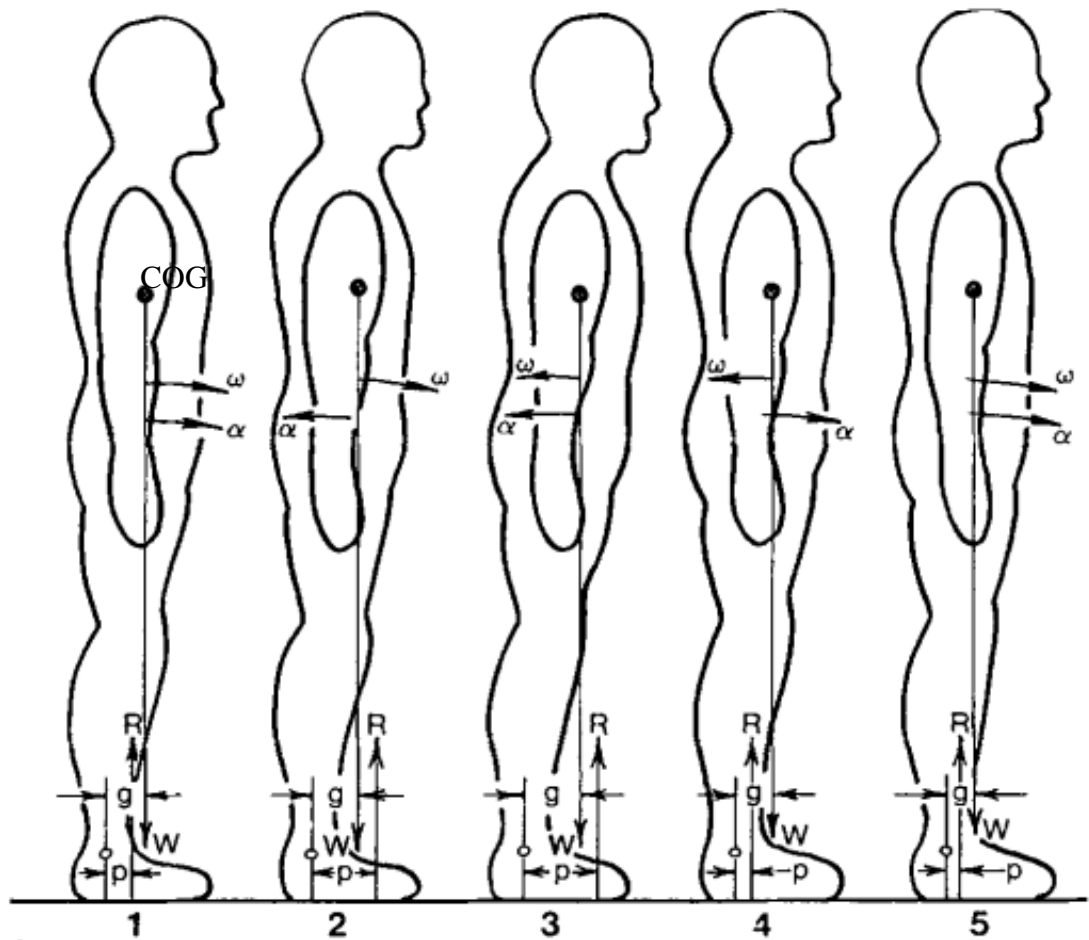


Figure 2.9. Winter (1995) has used this figure to show, in five different points in time, variations of distance between centre of gravity (COG) and the ankle (g), distance between centre of pressure (COP) locations and the ankle (p), angular accelerations (α), and angular velocity (ω) of an individual swaying back and forth while standing quietly (modified based on a figure reproduced from Winter, 1995, p. 195).

At time point 1, the body is tilting forward. Assuming the moment produced by body weight and gravity (i.e. $W \times g$) is greater than the corrective moment produced by the ground reaction force (R) (i.e. $W \times g > R \times p$), the body sways forward with a clockwise α and ω . The CNS will integrate the information from sensory systems and increase activation of the plantarflexors, the calf muscles, to generate the corrective torque to maintain a stable, upright posture.

The increase in the activation of the plantarflexors continues until the moment produced by body weight is smaller than the corrective moment produced by the ground reaction force (i.e. $R \times p$), as shown in time point 2. At this point, α is anti-clockwise and the magnitude of the clockwise ω is reducing. A further increase in the activation of the plantarflexors will increase the magnitude of anti-clockwise α , resulting in an anti-clockwise ω and bringing the body toward a neutral position (time point 3).

When the body leans backward, the CNS senses that the posterior shift of the centre of mass needs to be adjusted. The CNS decreases the activation of the plantarflexors such that the moment produced by body weight is greater than the corrective moment produced by the ground reaction force, (time point 4). At this time, α is clockwise and the magnitude of the anti-clockwise ω is reducing. A decrease in the activation of the plantarflexors continues until both α and ω are clockwise (time point 5), and the body sways forward and returns to the condition similar to time point 1. These five points in time repeat as the body sways forward and backward.

It can be seen that maintaining balance under bipedal quiet standing requires adjustments of corrective torque about the ankles. These adjustments are primarily produced by changing the activation levels of leg muscles about the ankles, such as SOL. Low-frequency, low-acceleration motion is likely to challenge the balance of individuals (for example Burton et al., 2011). Under such situations, the TA may be activated to prevent the body from falling backward. Hence, measuring the activation levels of leg muscles, particularly SOL and TA, will assist with understanding the importance of maintaining balance during the performance of a manual task when an individual is exposed to wind-induced building motion.

2.8 Criteria or recommendations for occupant response to wind-induced building motion

Up to early 1970s, constructions of wind-sensitive buildings were uncommon. Irwin (1975) commented that the public generally expected that buildings would not move under wind actions. Perceptible wind-induced building motion in office or residential buildings was generally considered to be unacceptable. The public held this impression because buildings at the time were usually short, massive, and/or built with material that provided effective damping such that the buildings were not prone to wind-induced building motion. As technology for building design and construction became more advanced, engineers and building designers used new structural systems and materials to construct taller and more slender buildings. These advances in building design and construction technology resulted in buildings that were more structurally flexible than their predecessors, resulting in larger and more perceptible wind-induced building motion. This wind-induced building motion became one of the biggest concerns to those who could not accustom or accept perceptible wind-induced building motion. The structural performance of buildings however was mainly classified in terms of allowable stresses and deflections and recommendations regarding the effects of building motion on occupants were vague. Further, there was no guidance as to what constituted an acceptable level of motion. Hence, Irwin (1975) highlighted the needs for formulating a code of practice that governs allowable motion of buildings to create a comfortable building environment.

Irwin (1975) re-analysed all available data that investigated the effects of motion including, but not limited to, actual and simulated building motion on human responses, aiming to formulate a code of practice that governs allowable motion of buildings. Based on these re-analyses, Irwin (1975) determined that human perception of motion is governed largely by acceleration up to about 1.9 Hz. Therefore, acceleration can be used to assess perceptible and tolerable levels of wind-induced building motion for frequencies that are generally below 1 Hz. Further, Irwin (1975) concluded that a perceptible level of motion does not represent the tolerable limit and an appropriate limit imposed upon wind-induced building motion should consider the effects of motion frequency, mode of vibration, length of storm peaks, return period of storm, and building use.

Irwin (1975) then proposed two acceleration curves, one curve which balanced perceptible motion and motion that causes discomfort, to determine acceptable building motion for the average population, and a second curve that was applicable to special buildings, such as hospital, in which the level of motion needed to be kept below perception thresholds as occupants of those buildings may find even motion at the threshold of human perception highly disturbing and undesirable. The second curve was based on peak acceleration because it is the peak that triggers perception of motion. As Irwin (1978) used the same set of data to derive a set of acceleration curves for various building usages, details of the acceleration curves included in Irwin (1975) are presented in the following paragraphs describing Irwin (1978) to avoid duplication.

Expanding on Irwin (1975), Irwin (1978) proposed a series of perceptible and acceptable acceleration curves for various building usages. These perceptible and acceptable acceleration curves formed the basis for formulating the “Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures, to low-frequency horizontal motion (0.063 to 1 Hz), ISO 6897:1984” (International Organization for Standardization, 1984).

For buildings used for general purposes, Irwin (1978) proposed an acceptable maximum RMS acceleration of horizontal motion during the worst 10 minutes of a windstorm with a return period of at least 5 years, represented by curve 1 of Figure 2.10. RMS acceleration, rather than peak acceleration, was used for the acceleration curve because building occupants are more influenced by the level of acceleration averaged over a period of a storm peak than by individual events represented by peak acceleration. A period of 10 minutes was chosen to determine RMS acceleration because occupants generally remember storms that have a duration in excess of 10 minutes. Based on the findings of Hansen et al. (1973), Irwin (1978) chose a return period of five years because occupants are thought to unlikely to complain about building performance if such a level of motion recurs only once every five years, on average. It is noteworthy that the suggested acceptable maximum RMS acceleration for buildings used for general purposes, that is curve 1 of Figure 2.10, was established based on perception and complaint rate; it did not consider the effects of horizontal motion on the performance of manual tasks. Goto et al. (1990) found that work performance decreased when the level of acceleration was greater than 4 milli-g under circular motion conditions at 0.23 Hz. This acceleration level was considered acceptable according to curve 1 of Figure 2.10. Therefore, curve 1 of Figure 2.10, may underestimate the effects of horizontal motion on the performance of manual tasks.

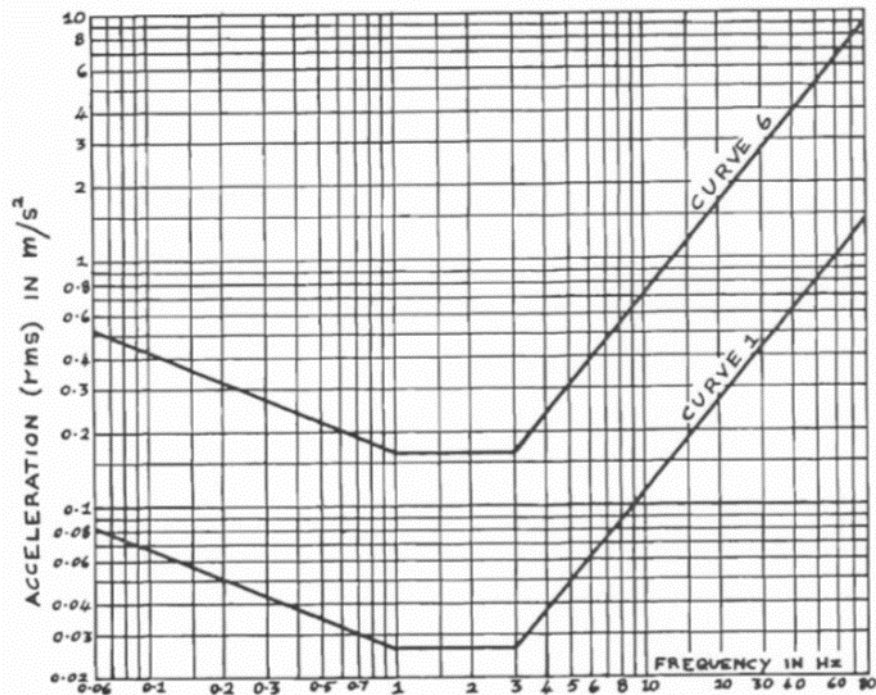


Figure 2.10. Maximum RMS acceleration of storm-induced horizontal motion suggested for buildings used for general purposes (Curve 1) and for offshore structures for non-routine duties and bridges (reproduced from Figure 2 of Irwin, 1978).

Irwin (1978) further proposed three recommendations for using the suggested acceptable maximum RMS accelerations for horizontal motion. First, in situations where motion occurs simultaneously at several frequencies, the acceleration magnitude at each frequency should be evaluated and assessed separately. Second, if the return period of motion at the suggested acceleration magnitudes decreased from five years to one year, the complaint rate for the motion would increase from 2% to 12%. Irwin (1978) however did not provide any justifications nor supporting evidence for this suggested higher percentage of complaint. Third, the suggested acceptable maximum RMS acceleration of horizontal motion did not consider the effects of acoustic noise that may exaggerate the feelings caused by motion. In situations where acoustic noise exists, magnitudes of the suggested acceptable maximum RMS acceleration of horizontal motion should be reduced. However, Irwin (1978) did not provide evidence to support the recommendation.

Irwin further suggested that for offshore structures where non-routine tasks have to be executed, a skilled operation has to be carried out, or where some decisions have to be made, acceptable maximum RMS acceleration of horizontal motion should be limited below curve 6 of Figure 2.10. This acceptable maximum RMS acceleration of horizontal motion for offshore structures is 6 times greater than that suggested for buildings used for general purposes. Irwin (1978) further noted that for routine tasks such as drilling performed on offshore structures, the acceptable magnitude of acceleration should be governed by whether the machinery can be operated but not by the effects of the motion on human responses. The author however did not provide any evidence to support this argument.

Irwin (1978) also suggested acceptable RMS acceleration of horizontal motion for buildings subjected to frequently induced building motion. This criterion is applicable to buildings in which precision work is carried out and for special buildings such as hospital operating theatres. Irwin (1978) claimed that the criterion for such buildings is related to the motion perception thresholds of people of average sensibility. Therefore, a lower perception threshold of motion should be used, as shown in base curve 1 of Figure 2.11. It should be noted that Irwin (1978) did not provide any evidence to support why perception thresholds of motion of people of average sensibility should be used to establish a criterion for the designs of buildings in which precision work is carried out and for special buildings. Furthermore, the acceptable maximum RMS acceleration of horizontal motion was suggested for special structures that are apparently required to be stationary. Therefore, the suggested acceptable RMS acceleration of horizontal motion is not applicable to buildings for general purposes.

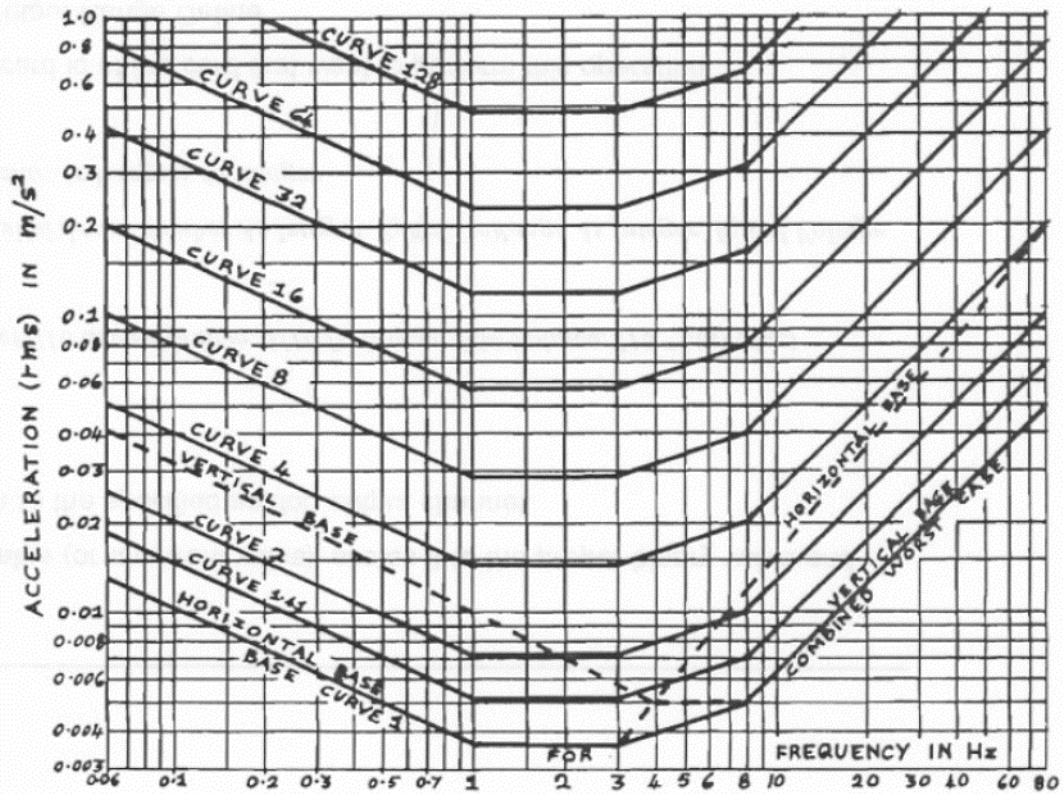


Figure 2.11. RMS acceleration magnitudes of perception to horizontal and vertical motion, that is, the horizontal base curve and the vertical base curve (reproduced from Figure 3 of Irwin, 1978).

The International Organisation for Standardisation (ISO) published the “Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and offshore structures, to low-frequency horizontal motion (0.063 to 1.0 Hz), ISO 6897:1984” for the assessment of occupant comfort (International Organization for Standardization, 1984). ISO 6897:1984 was developed largely based on the work of Irwin (1975 and 1978) quoted in the previous paragraphs. Four RMS acceleration magnitude curves were suggested for frequencies ranging from 0.063 to 1 Hz. The first satisfactory RMS acceleration magnitude curve of horizontal motion was suggested for buildings used for general purposes, represented by curve 1 of Figure 2.12, based on the worst 10 consecutive minutes of a windstorm with a return period of at least five years. Further, no more than 2% of people occupying the parts of the building where the motion is greatest would complain about the motion (International Organization for Standardization, 1984).

Based on Irwin (1978), ISO 6897:1984 also suggested that the percentage of people occupying the parts of the building where motion is greatest would increase from 2% to 12% if the return period of the storm decreased from five years to one year. ISO 6897:1984 further suggested that, to obtain a probable adverse complaint level of 2 % for acceleration magnitude with a return period of one year, a factor of 0.72 should be applied to curve 1 of Figure 2.12, that is, the satisfactory RMS acceleration magnitudes suggested for a return period of five years.

For off-shore fixed structures where non-routine or skilled manual operations are carried out, the satisfactory RMS acceleration magnitudes of horizontal motion for infrequently induced horizontal motion is shown in curve 2 of Figure 2.12. As suggested by Irwin (1978), these satisfactory RMS acceleration magnitudes of horizontal motion are six times higher than curve 1 that is suggested for buildings used for general purposes.

For buildings subjected to regularly occurring horizontal motion, the RMS acceleration criteria were related to perception thresholds of horizontal motion for sensitive and for average humans, that is to the lower (curve 1) and average (curve 2) thresholds as shown in Figure 2.13. The lower thresholds (curve 1) are applicable to buildings where an environment is required to be apparently stationary while the average thresholds (curve 2) are applicable to special buildings where routine precision work is carried out. The average perception thresholds (curve 2) are four times greater than the lower perception thresholds (curve 1).

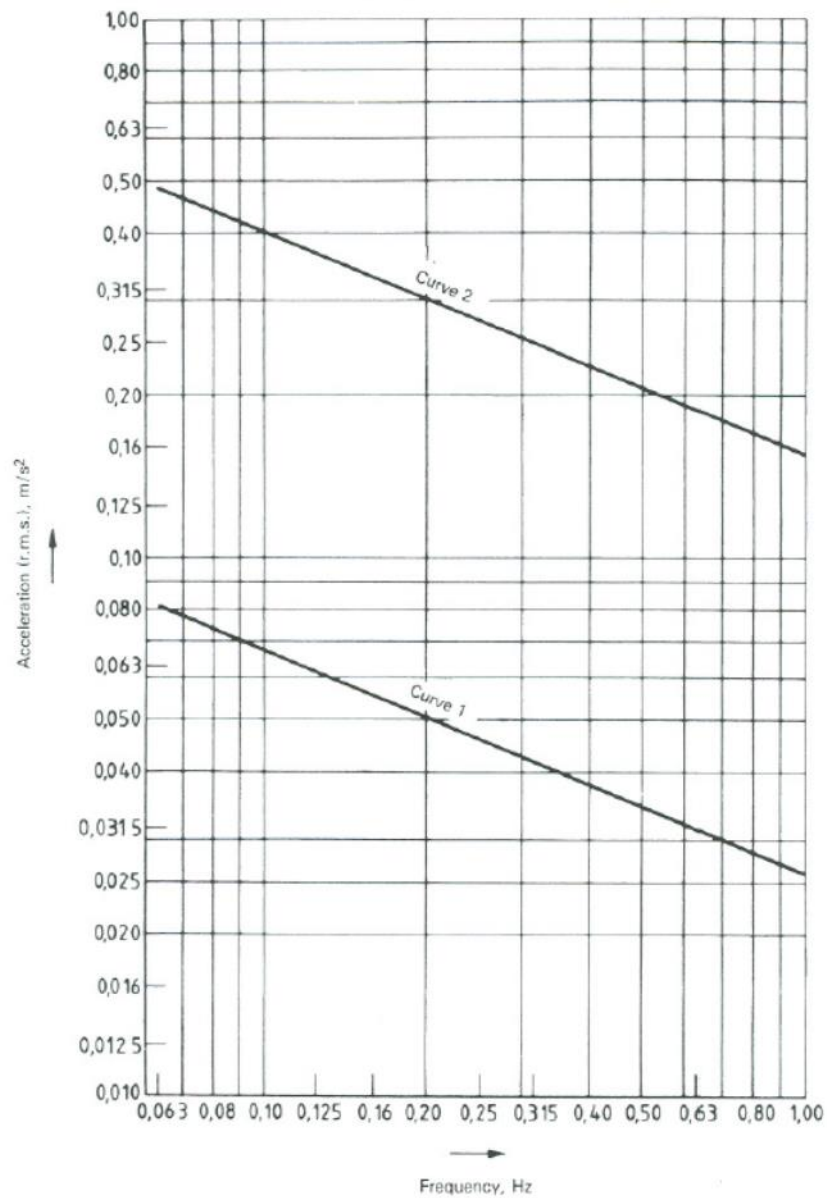


Figure 2.12. Suggested satisfactory magnitudes of horizontal motion of buildings used for general purposes (curve 1) and of off-shore fixed structures (curve 2) (reproduced from Figure 1 of International Organization for Standardization, 1984).

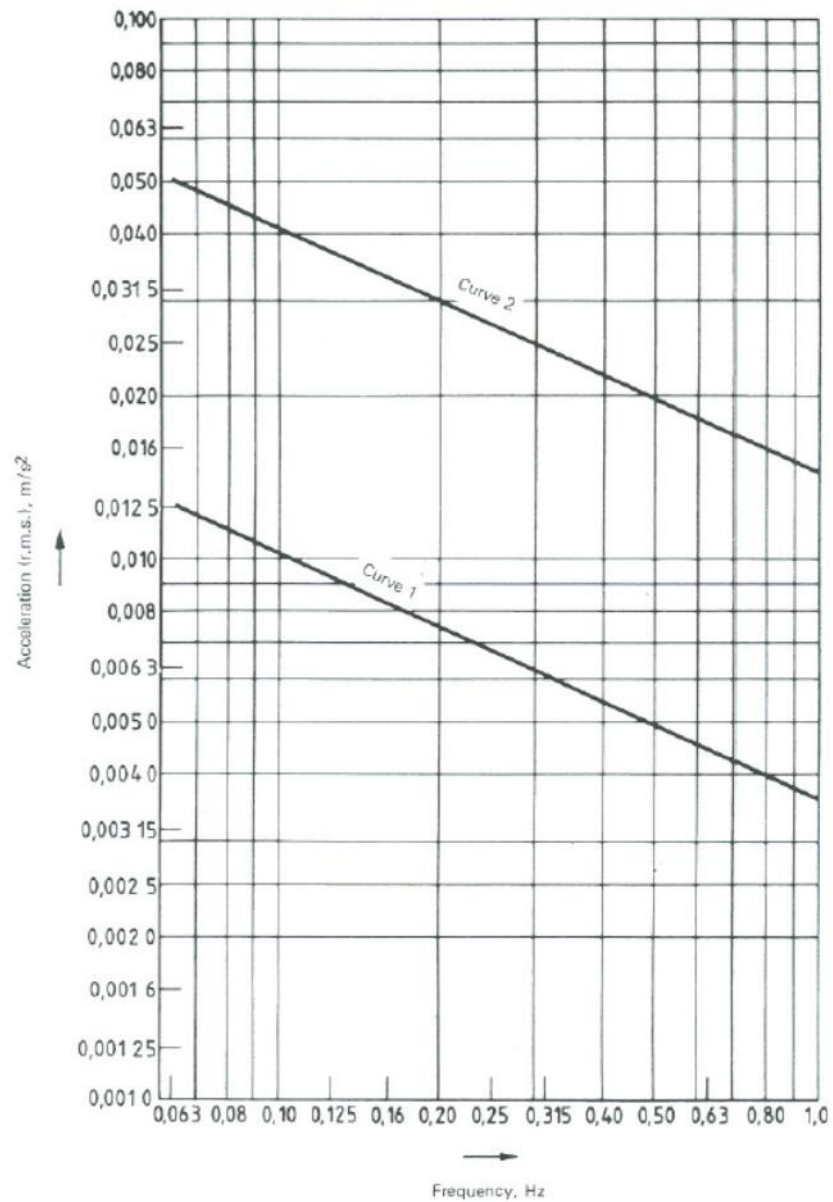


Figure 2.13. Lower (curve 1) and average (curve 2) perception thresholds of horizontal motion (reproduced from Figure 2 of International Organization for Standardization, 1984).

Melbourne and Palmer (1992), realising that criteria based on the standard deviation of acceleration ignore the probability distribution of peak accelerations that vary greatly between a sine wave and typical wind-induced building motion, developed criteria for occupant comfort in terms of peak accelerations as a function of motion frequency and return period. Development of the peak acceleration criteria was based on the satisfactory RMS acceleration magnitudes proposed for buildings for general purposes for the worst 10 consecutive minutes of a storm with a return period of five years (International Organization for Standardization, 1984). Melbourne and Palmer (1992) firstly fitted the satisfactory RMS acceleration magnitudes of horizontal motion using Equation 2.2.

Equation 2.2

$$\sigma_{\ddot{x}} = \exp(-3.65 - 0.41 \ln(n))$$

where

$\sigma_{\ddot{x}}$ is the standard deviation of acceleration of horizontal motion
 n is frequency of horizontal motion.

Assuming that wind-induced building motion is a normally distributed process, Melbourne and Palmer (1992) derived peak acceleration from standard deviation acceleration using Equation 2.3.

Equation 2.3

$$\hat{\ddot{x}} = g \sigma_{\ddot{x}}$$

where

g is the peak factor $\approx \sqrt{2 \ln nT}$ for a normally distributed process
 n is frequency of horizontal motion.
 T is the duration in seconds (i.e. for 10 minutes, $T = 600$ seconds).

Melbourne and Palmer (1992) also proposed Equation 2.4 to transform acceleration for a return period of five years to other return period, R.

Equation 2.4

$$\frac{\text{response for return period of R years}}{\text{response for return period of 5 years}} = 0.68 + \frac{\ln(R)}{5}$$

Combining Equation 2.2 to Equation 2.4, the peak acceleration for occupant comfort can be expressed as a function of return period and motion frequency as shown in Equation 2.5.

Equation 2.5

$$\hat{x} = \sqrt{2 \ln nT} \left(0.68 + \frac{\ln(R)}{5} \right) \exp(-3.65 - 0.41 \ln(n))$$

The peak acceleration criteria however did not account for effects of motion on performance of manual tasks conducted in building for general purposes because the peak acceleration criteria for occupant comfort was based on ISO 6897:1984.

Isyumov (1993) realised that it was economically unfavourable to keep wind-induced building motion below the perception threshold, therefore he formulated a set of assessment criteria as questions: how much and how frequently can the perception threshold be exceeded without degrading occupant comfort and confidence? Isyumov (1993) proposed a set of criteria that are higher than perception thresholds to assess acceptability of wind-induced building motion, as shown in Table 2.4.

The acceleration criteria are based on hourly peak acceleration determined at the top floor of the building for storms with a return period of one year. The return period of one year was used to accommodate regions where the wind climate is influenced by tropical storms such as hurricanes, typhoons or cyclones. Isyumov (1993) also proposed criteria for a return period of 10 years for comparison, which are also shown in Table 2.4.

Table 2.4. Guidelines for evaluation acceptability of wind-induced building motion proposed by Isyumov (1993, 1995).

	For a recurrence rate of one year	For a recurrence rate of ten years
Step 1 Resultant hourly peak horizontal acceleration at the top floor considering both translational and torsional motion <ul style="list-style-type: none"> • Residential buildings • Office buildings • Hotels 	5 – 7 milli-g 9 – 12 milli-g 7 – 9 milli-g	10 – 15 milli-g 20 – 25 milli-g 15 -20 milli-g
Step 2 Hourly peak torsional velocity at the top floor for both office and residential buildings	< 1.5 milli-radian per second	< 3 milli-radian per second

The criteria were independent of motion frequency. This was justified by considering the variation of perception threshold across frequency of the two percent of the most sensitive individuals, as determined by Shioya et al. (1992). Shioya et al. (1992) found that the 2nd percentile perception thresholds in the frequency range between 0.125 to 0.315 Hz were nearly constant. Compared with the individual difference on perception threshold, the variation of perception threshold across this relatively small range of frequency was negligible. Furthermore, Isyumov (1993) suggested that the motion perception in buildings appeared to be strongly influenced by audio and visual cues and these cues were more likely to be dependent on motion velocity rather than on the jerk. Therefore, Isyumov (1993) proposed that the criteria could be independent of motion frequency.

Isyumov (1993) also proposed different criteria for office and residential buildings. This accounted for how occupants generally use office and residential buildings. For office buildings, occupants usually stay for a relatively short period. Further, office occupants are expected to vacate their office buildings during severe storms. However, residential occupants are expected to stay in residential buildings continuously for long durations and return to their homes during unusual weather events. These circumstances implied that office occupants can be expected to have a higher tolerance of wind-induced building motion than residential occupants. Therefore, the criteria for residential buildings were more stringent than those for office buildings.

Isyumov's criteria to assess acceptability of building motion involved two steps. First, the hourly peak resultant acceleration for a return period of one year at the top floor of the building should be within or below the criteria for office or residential occupancies suggested in Table 2.4. This resultant acceleration includes the effects of both translational and torsional motion. This first step addressed the issues caused by motion-induced discomfort. Second, the hourly peak torsional velocity for a return period of one year at the top occupied floor should be less than 1.5 milli-radian per second. This requirement aimed to limit visual cues which are particularly pronounced in the presence of wind-induced torsional motion. Isyumov (1995) later suggested criteria for hotel buildings, which are also summarised in Table 2.4. Isyumov (1995) also suggested that wind-induced building motion should be assessed for a return period of 10 years.

An advantage of Isyumov's criteria was that it introduced limitations on torsional motion to reduce the effects of visual cues not considered by ISO 6897:1984. However, it is worth noting that the criteria do not consider the effects of wind-induced building motion on the performance of manual tasks. Furthermore, the criteria are independent on frequency which may mask the effects of motion on the resonant characteristics of body sway which in turn may adversely affect the performance of manual tasks.

"Guidelines for the Evaluation of Habitability to Building Vibration, AIJ-GEH-2004" was published in 2004 (Architectural Institute of Japan, 2004). Based largely on the perception thresholds determined by studies conducted by a group of Japanese researchers (including Kanda et al., 1988; Nakata et al., 1993; Shioya et al., 1992; Tamura et al., 2006), AIJ-GEH-2004 proposed five frequency-dependent peak acceleration curves for frequencies ranging from 0.1 to 5 Hz, as shown in Figure 2.14. The five peak acceleration curves (H-10 to H-90) correspond to perception thresholds with perception probabilities ranging from 10 percent to 90 percent.

AIJ-GEH-2004 does not specify allowable levels or guidelines for evaluating the habitability of buildings. Instead, AIJ-GEH-2004 allows building owners and designers to choose peak acceleration curves for any perception probabilities for habitability evaluation. For example, building owners and designers of a 0.3 Hz building may limit the one-year return period peak acceleration to 7 milli-g, if 90%, on average, of the occupants are expected to perceive wind-induced building motion once per year. However, if the percentage of occupants who is expected to perceive the motion is reduced to 70%, on average, the one-year return period peak acceleration may be limited to 5 milli-g. Furthermore, AIJ-GEH-2004 recommends applying the suggested peak acceleration curves for habitability evaluation with a return period of one year. Similar to other acceleration criteria described earlier, AIJ-GEH-2004 does not account for any effects of wind-induced building motion on human wellbeing and the performance of manual tasks.

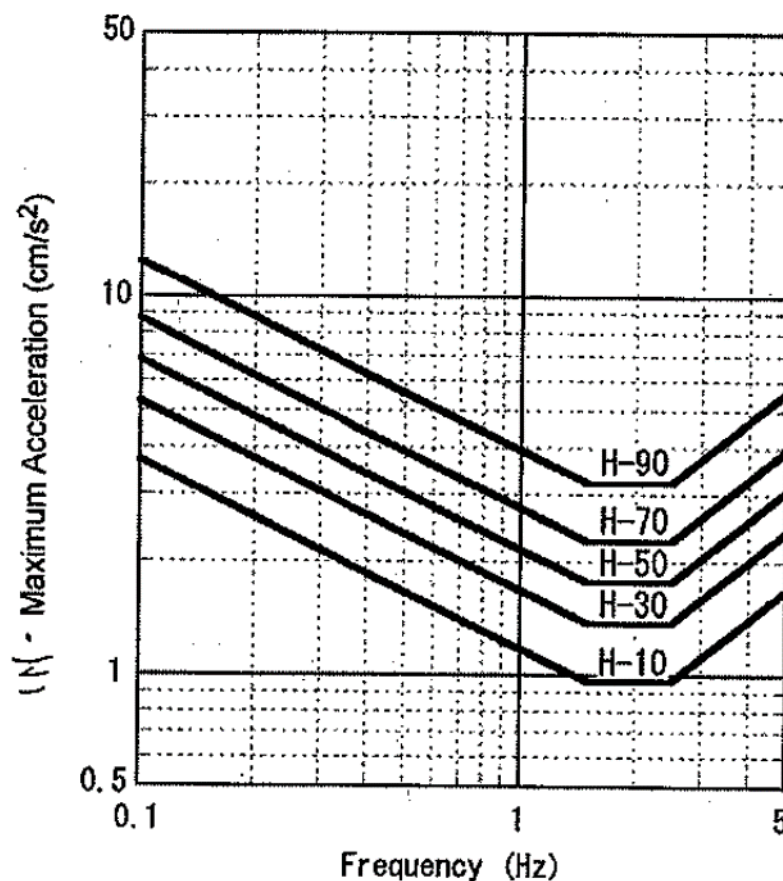


Figure 2.14. Acceleration magnitudes for various perception probabilities suggested in AIJ-GEH-2004 (reproduced from Figure 1 of Nakamura et al., 2004).

The International Organisation for Standardisation (ISO) introduced two frequency dependent peak acceleration criteria in “Bases for design of structures – Serviceability of buildings and walkways against vibration, ISO 10137:2007” for office and residential buildings (International Organization for Standardization, 2007). ISO 10137:2007 suggested that the curves should be applied to evaluate habitability due to the effects of wind-induced building motion with a return period of one year. The peak acceleration criteria covered a frequency range between 0.06 to 5 Hz, as shown in Figure 2.15. The peak acceleration magnitudes proposed for residential buildings were 2/3 of those proposed for office buildings. Furthermore, the peak acceleration magnitudes proposed for residential buildings were close to the perception probability of 90% suggested in AIJ-GEH-2004. It is noteworthy that the acceleration criteria proposed in ISO 10137:2007 focus on the perceptions of building occupants but not the effects of wind-induced building motion on human wellbeing and the performance of manual tasks.

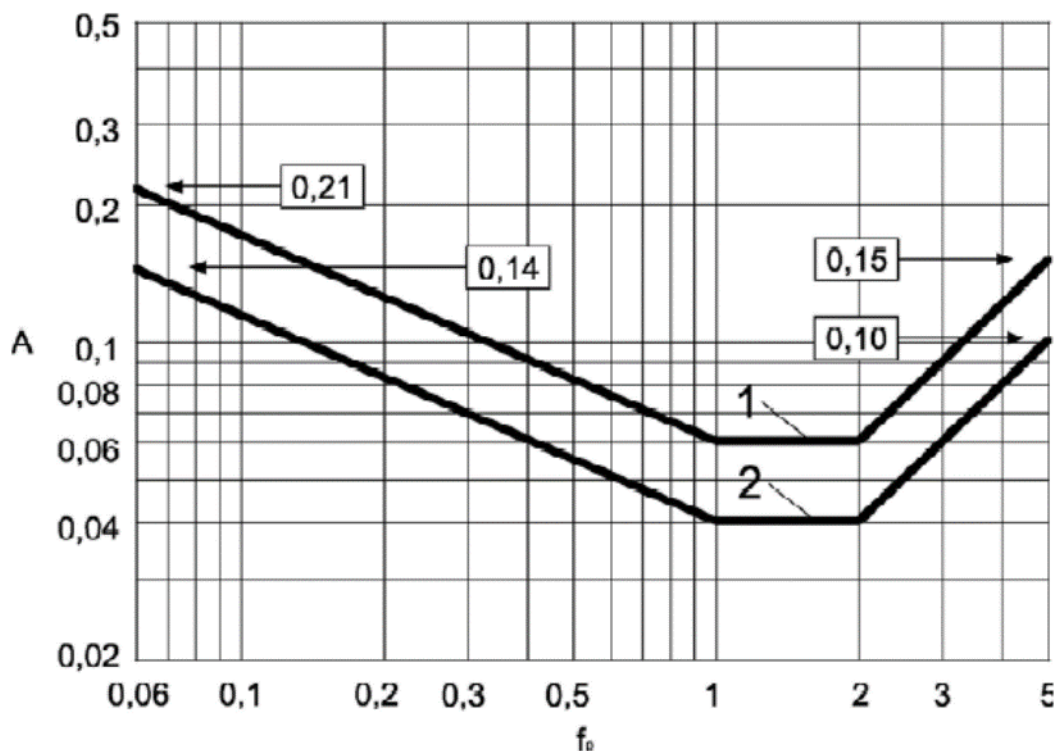


Figure 2.15. Peak acceleration curves suggested for evaluating the acceptability of wind-induced building motion with a return period of one year for office (curve 1) and residential (curve 2) buildings (reproduced from Figure D.1 of International Organization for Standardization, 2007).

Recently, the American Society of Civil Engineers (ASCE) published a monograph on occupant response to wind-induced building motion and acceptability criteria for wind-excited tall buildings (Kwok et al., 2015). The monograph provided background information on a range of subjects such as acceptability criteria for wind-induced building motion. After reviewing acceptability criteria published by a number of standards organisations, the authors of the monograph realised that acceptable acceleration values varied greatly even after they have been standardised for comparison purposes. In the conclusions, the monograph suggests three peak acceleration thresholds for i) perception, ii) comfort and wellbeing, and iii) fear and safety as general guidelines.

For perception, the monograph suggested limiting peak acceleration below 5 milli-g. This acceleration level is perceptible to many occupants. However, this acceleration level is not likely to cause significant adverse occupant response or alarm, if such building motion does not occur frequently or continuously for an extended period of time. The peak acceleration limit for comfort and wellbeing threshold is 10 milli-g. However, the authors realised that occupants in buildings frequently exhibiting wind-induced motion for an extended period of time at such a level may object to such motion, particularly those prone to motion sickness. It is noteworthy that the authors did not clearly define the duration and frequency of occurrence that can cause adverse effects on occupants. The peak acceleration limit for fear and safety is 35-40 milli-g. This limit is severe enough to cause some occupants to lose their balance. Building motion at or above such levels should be avoided where possible.

A merit of these guidelines is that they offer comprehensive acceleration limits for assessing the habitability of buildings. The thresholds considered the acceleration limits for perception, for comfort and wellbeing, fear and safety. This is significantly different from the acceptability criteria for wind-induced building motion published earlier (for example Architectural Institute of Japan, 2004; International Organization for Standardization, 2007; Isyumov, 1995). However, the guidelines are relatively simple. Although they suggested the higher acceleration limit for fear and safety may be used for buildings with lower natural frequency, the acceleration limits for perception, comfort and wellbeing are independent of frequency. This is inconsistent with the majority of other acceptability criteria (for example, Architectural Institute of Japan, 2004; International Organization for Standardization, 1984, 2007). Further, the guidelines do not consider the effects of wind-induced building motion on the performance of manual tasks which form an important part of the daily activity of building occupants.

2.8.1 Summary

Engineers, building scientists, and researchers have established criteria and recommendations on acceleration magnitudes to address human responses to wind-induced building motion (for example Architectural Institute of Japan, 2004; International Organization for Standardization, 1984, 2007; Isyumov, 1995). Although these criteria and recommendations were established based on previous studies on human responses to real and/or simulated wind-induced building motion, they are significantly different from each other due to factors such as consideration of frequency dependency, return periods of strong wind events, usage of RMS or peak acceleration, consideration of types of occupancy, and with or without limiting torsional motion. Furthermore, applications of these criteria and recommendations may be very different. Some of them suggested curves for satisfactory acceleration magnitudes (for example ISO 6897:1984 and ISO 10137:2007) for serviceability limit state design. In contrast, AIJ-GEH-2004 provides acceleration magnitude curves corresponding to various perception probabilities that allow building owners, developers, and/or building design practitioners to choose at their own discretion in assessing building performance.

Overall, the current criteria and recommendations have been established based on perception thresholds and/or complaint rate/tolerance of wind-induced building motion for buildings used by the general population. Lamb et al. (2014) showed that wind-induced building motion can degrade work performance of building occupants. However, no criteria or recommendations consider the effects of building motion on manual task performance. Hence, further investigations on the effects of building motion on manual task performance are necessary.

2.9 Concluding remarks

Over the last five decades, researchers have conducted field studies and surveys of occupants in buildings subjected to strong wind or artificial excitations to determine human responses, in particular perception threshold, to wind-induced building motion. Results of these field studies have mainly focused on perception thresholds and/or tolerance to wind-induced building motion. Some of these studies, for example Hansen et al. (1973) and Goto (1983), have suggested that wind-induced building motion provokes motion sickness and adversely affects occupants' manual task performance. While these studies provided the most realistic building environments for determining human responses to wind-induced building motion, they are unable to establish a relationship between human response and motion frequency and acceleration. This is mainly attributable to the difficulties in installing instruments for measuring wind-induced building motion and recruiting participants in appropriate wind conditions, and the limited number of buildings being surveyed.

With the advantages of controllability in motion frequency and acceleration magnitudes, motion simulator studies have been used extensively to determine motion perception thresholds across a range of frequencies that are relevant to wind-induced building motion. Results of these motion simulator studies have generally suggested that perception thresholds generally decrease as frequency increases from 0.1 Hz to 1 Hz, recognising that perception to motion depends on motion frequency. Further, the results indicated that perception thresholds of individual generally follow log-normal distributions (for example Chen and Robertson, 1972; Tamura et al., 2006), thus providing useful information to formulate probabilistic based acceleration recommendations (for example Architectural Institute of Japan, 2004) that allows building owners and/or developers to use the recommendations to design a building based on their requirement on building performance.

Few studies have investigated the effects of low-frequency, low-acceleration motion on the performance of manual tasks. None of these studies established relationships between manual task performance and motion frequency and acceleration magnitudes, or determined the potential causes that adversely affect manual task performance. Furthermore, the findings of these studies are generally inconclusive. While Goto et al. (1990) concluded that low-frequency, low-acceleration motion of sufficiently high acceleration magnitudes degrades manual task performance, Burton et al. (2011), Irwin and Goto (1984), and Jeary et al. (1988) found no significant task performance degradations in their studies. These inconclusive findings may be attributed to the characteristics of participants, manual tasks, motion, or a combination of these factors.

Studies investigating the effect of wind-induced building motion on incidents of motion sickness or sopite syndrome are also very limited. The majority of these studies indicated that wind-induced building motion could provoke salient symptoms of motion sickness, such as nausea and vomiting (for example Burton et al., 2005; Goto, 1983; Hansen et al., 1973). However, a presentation of salient symptoms of motion sickness is likely to occur at high acceleration magnitudes that are more relevant to extreme windstorms. Recent studies showed that wind-induced building motion at low acceleration magnitudes are likely to provoke sopite syndrome in many building occupants (Lamb et al., 2013, 2014; Walton et al., 2011). Since low acceleration, wind-induced building motion occurs more frequently than extreme windstorms, symptoms of sopite syndrome are likely to appear more frequently than salient symptoms of motion sickness. Therefore, the incidence of sopite syndrome becomes an important issue related to human responses to wind-induced building motion. While Lamb et al (2014) investigated the relationship between the severity of sopite syndrome and subjective work performance and cognitive performance, no study has investigated the effect of sopite syndrome on manual task performance under motion conditions.

Criteria and recommendations have suggested acceleration magnitudes based on perception thresholds and/or tolerance of wind-induced building motion for buildings used by the general population (for example Architectural Institute of Japan, 2004; International Organization for Standardization, 1984, 2007). Although satisfactory acceleration magnitudes were suggested for off-shore fixed structures where non-routine or skilled manual operations were carried out (International Organization for Standardization, 1984), there is neither criterion nor recommendations suggesting satisfactory acceleration magnitudes when considering the manual task performance of the general population in buildings used for general purposes. This may be attributed to the lack of research data for formulating criteria and recommendations addressing the effects of wind-induced building motion on manual task performance. Further, the criteria and recommendations do not consider the effects of sopite syndrome which can be an important adverse effect to occupants in wind-induced building motion environments.

The performance of manual tasks in transportation environments has been extensively studied. Although the motion in transportation environments is significantly different from wind-induced building motion, these studies are comprehensive, hence they can provide insights into the effects of wind-induced building motion on the performance of manual tasks. One of the studies showed the effects of vertical translational motion on a continuous tracking task was more significant than on a discrete tracking task (McLeod and Griffin, 1988). This explained why Goto et al. (1990) could use a continuous manual task to measure degraded performance while Burton et al. (2011) could not, as a discrete manual task was used. It is suggested that a continuous manual task should be used to investigate the performance of manual tasks under wind-induced building motion conditions.

A behavioural model used to explain the effects of motion on a continuous tracking task performance was proposed by McLeod and Griffin (1989). The behavioural model indicated that tracking task performance was likely to be affected by vibration breakthrough, visual impairment, neuro-muscular interference, central effects, and secondary effects such as increased workload, changes in strategy, and active compensation. This behavioural model may assist researchers to understand the mechanisms causing manual task performance degradation in wind-induced building motion environments. It should be noted that central effects is one of the mechanisms that may cause degradation in manual task performance. In addition, Lamb et al. (2014) showed that subjective work performance and cognitive performance decreased as the severity of the motion sickness or sopite syndrome increased. Effects of motion sickness or sopite syndrome on manual task performance should be emphasised. Further, understanding the activations of leg muscles responsible for maintaining a stable upright standing posture may provide insights into the influence of body sway on manual task performance under wind-induced building motion conditions.

CHAPTER 3

METHODOLOGY FOR INVESTIGATION OF EFFECTS OF LOW-FREQUENCY, LOW-ACCELERATION MOTION ON MANUAL TASK PERFORMANCE

3.1 Introduction

Chapter 2 has reviewed previous studies investigating the effects of low-frequency, low-acceleration motion, including wind-induced building motion, on human responses. The majority of previous studies investigated the effects using field studies and surveys of occupants conducted in buildings subjected to strong wind or using motion simulator experiments. Furthermore, none fully explored the effects of low-frequency, low-acceleration motion and sopite syndrome on manual task performance.

A purpose-built motion simulator at the Hong Kong University of Science and Technology (HKUST) offered an opportunity to control motion frequency and acceleration to investigate the human responses to low-frequency, low-acceleration motion. This thesis presents a series of motion simulator experiments conducted to investigate the effects of low-frequency, low-acceleration motion on manual task performance. The effects of motion sickness and/or sopite syndrome on manual task performance were also investigated. The activation levels of leg muscles, particularly the soleus (SOL) and tibialis anterior (TA), the two leg muscles which are primarily involved in maintaining balance in the fore-aft direction, were measured to provide evidence to reveal the effects of motion and sopite syndrome on manual task performance and demonstrate whether compensatory action was carried out by participants under low-frequency, low-acceleration motion conditions.

This chapter outlines the capacity and calibration of the motion simulator. The main focus is the presentation of an experiment protocol designed to investigate the effects of acceleration, frequency, motion sickness and/or sopite syndrome severity, motion direction, and gender on manual task performance. The experiment protocol was also designed to investigate the effects of performing a manual task, acceleration, frequency, and motion sickness and/or sopite syndrome severity on the activation levels of soleus (SOL) and tibialis anterior (TA), the two leg muscles involved in maintaining balance.

3.2 Specifications of the motion simulator

In accordance with the studies reviewed in Chapter 2 of this thesis, a purpose-built motion simulator was needed to investigate the effects of low-frequency, low-acceleration motion on manual task performance. A set of specifications was proposed for designing a motion simulator to investigate occupant responses to wind-induced building motion (Denoon et al., 2001; Kwok and Hitchcock, 2008). The specifications suggested that the motion simulator should be able to i) reproduce bi-directional motion with both orthogonal axes controlled independently; ii) reproduce motion at frequencies in the range from 0.05 Hz to 1 Hz; and iii) reproduce sinusoidal and random motion free from high frequency vibration or noise. Furthermore, the specifications stipulated the motion simulator should have a test platform or test room with minimum dimensions of 3 meters \times 3 meters and be demountable for transportation.

The motion simulator was designed to the specifications (Denoon et al., 2001; Kwok and Hitchcock, 2008). The test platform of the motion simulator is shown schematically in Figure 3.1. The test platform is supported on two pairs of custom-built sliding bearings riding on precision machined and levelled rails. The maximum displacement amplitudes of the test platform in one direction (y-axis) is ± 800 mm and in the orthogonal direction (x-axis) is ± 400 mm. The maximum displacement amplitude of ± 800 mm allows the test platform to generate a maximum acceleration of around 30 milli-g at a frequency of 0.1 Hz. This motion condition represents an acceleration level which can cause discomfort to a significant number of people at a natural frequency as expected for buildings up to 700 meters in height. At a frequency of 0.05 Hz, the test platform can generate a maximum acceleration of 8 milli-g, which is expected to be perceptible to most people in a building with a height of 1,000 meters or more. The capacity of the motion simulator is shown in Figure 3.2. The motion simulator also provides flexibility to simulate realistic building motion along either one or two orthogonal axes at various combinations of frequency and acceleration of motion. A control centre controls the motion of the motion simulator by inputting prescribed test signals to the drive mechanisms of the two axes independently. The drive mechanisms are based on DC motors driving the test platform through high-precision ball screws. An anti-yaw device guides the planar motion of the test platform.

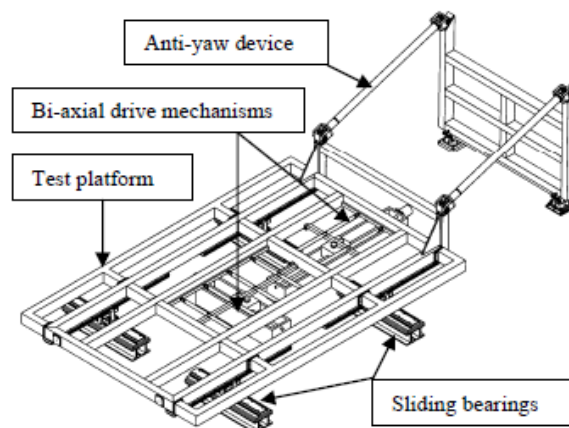


Figure 3.1. A schematic diagram of the test platform of the motion simulator at the Hong Kong University of Science and Technology (HKUST).

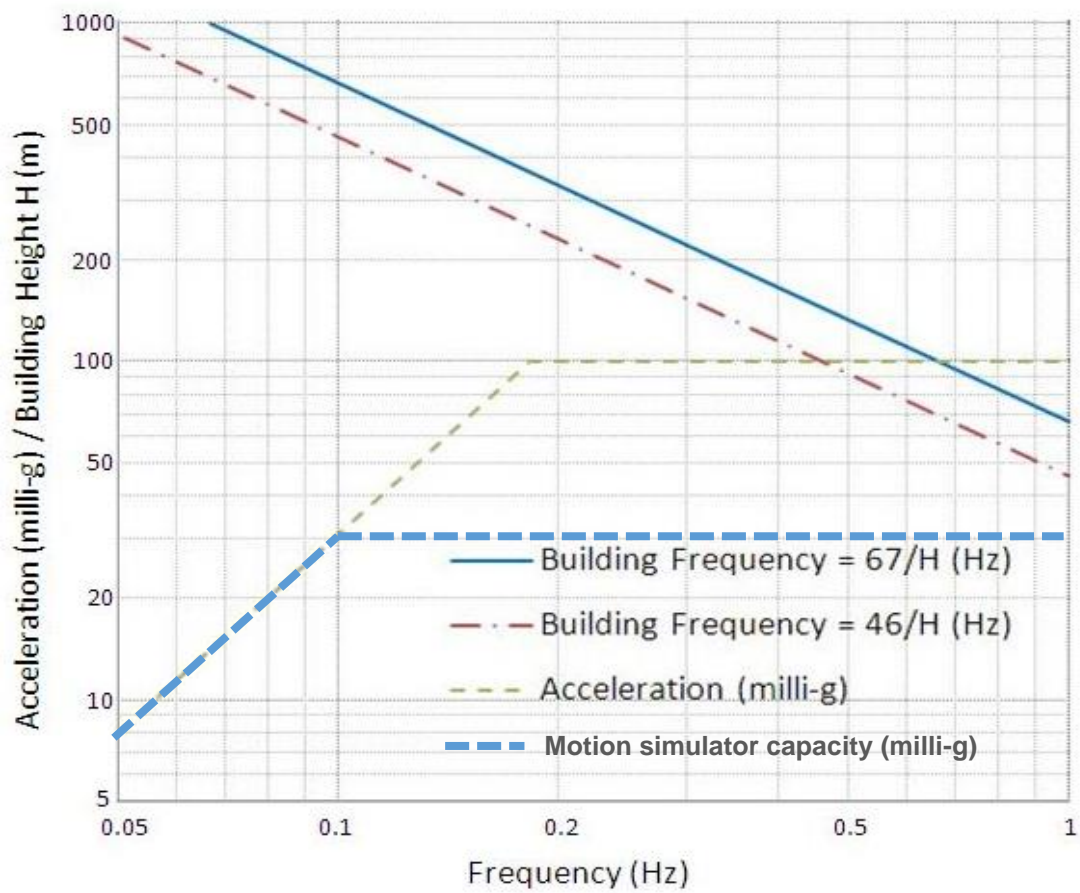


Figure 3.2. Capability of motion simulator at HKUST (reproduced from Kwok and Hitchcock, 2008).

Representative external and internal views of the motion simulator are shown in Figure 3.3 and Figure 3.4 respectively. The test room can be configured and decorated to simulate comfortable working or other test environments. It can be fitted with six workstations used for either occupant comfort or task performance investigations. An air-conditioner was installed in the test room to maintain a temperature of 25 degree Celsius for participants.



Figure 3.3. External view of motion simulator.



Figure 3.4. Internal view of motion simulator.

3.3 Calibrations of the motion simulator

A displacement calibration was conducted to verify the accuracy of sinusoidal motion reproduced by the motion simulator. The motion simulator was instructed to reproduce a set of designated sinusoidal motion (input). A digital camera (Panasonic Lumix DMC-GF2), a laser pointer, and a scale were used in the displacement calibration to measure the peak displacements (output) of each motion cycle. An experimental setup for the displacement calibration is shown in Figure 3.5.

During the displacement calibration, the laser pointer was aimed on the scale mounted on the ground. The digital camera was used to record the location of the laser light dot on the scale when the motion simulator was travelling during motion conditions. Videos were recorded at 30 frames per second and a resolution of 1080p (1920x1080 pixels), which is adequate for visually determining the peak displacement of all motion cycles. Figure 3.6 shows a view of the laser light dot shining on the scale when the motion simulator was stationary at the origin. Positive and negative peak displacements of all motion cycles were measured relatively to the origin. Accuracy of the peak displacement measurements were rounded to the nearest 1 mm.

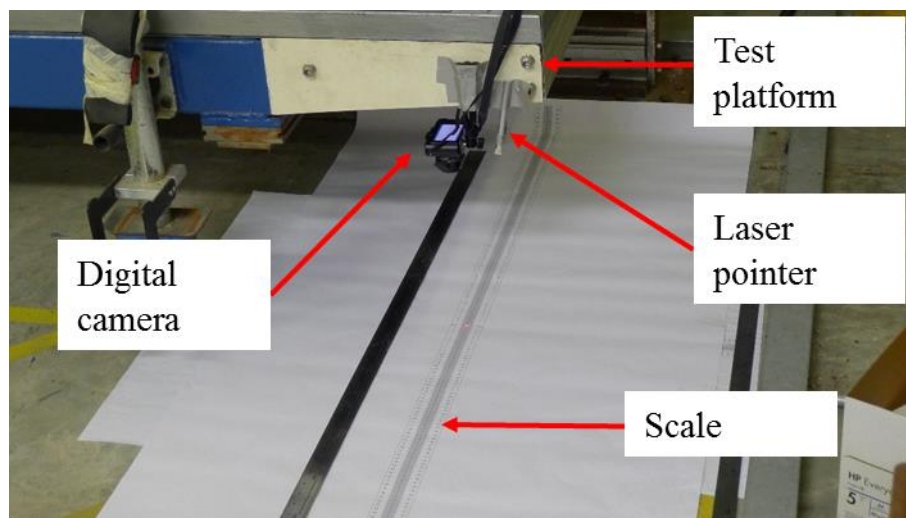


Figure 3.5. Experimental setup for displacement calibration.

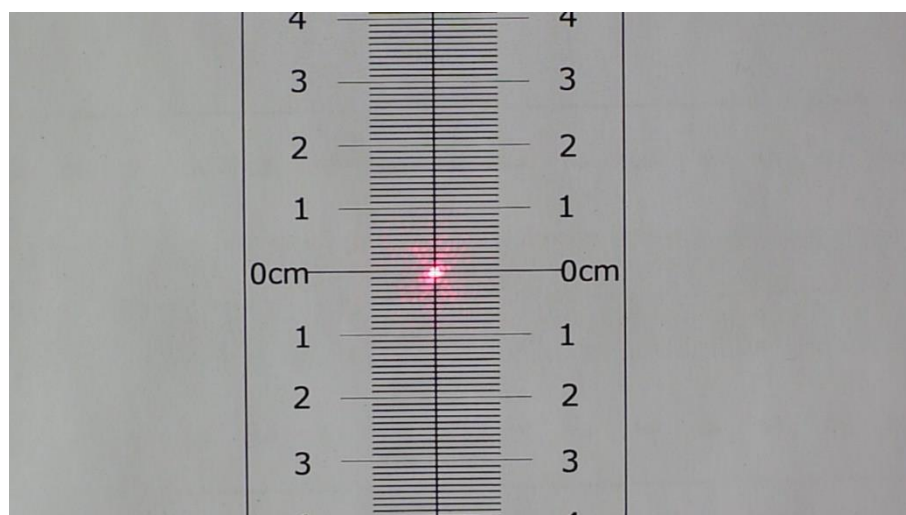


Figure 3.6. A view of a laser light dot shining on the scale.

The motion simulator was calibrated at two peak acceleration magnitudes of 6 and 30 milli-g for both x- and y- axes. At 30 milli-g, six frequencies were tested at 0.10, 0.16, 0.25, 0.40, 0.63, and 1.00 Hz for the y-axis. Due to a displacement limit of ± 380 mm, the x-axis could only be calibrated down to 0.14 Hz. The x-axis was tested at 0.14, 0.16, 0.25, 0.40, 0.63, and 1.00 Hz. As this thesis needed to measure manual task performance at 30 milli-g, 0.1 Hz (details of the tested motion conditions are presented in Table 3.2), all experiment conducted for this thesis was conducted along the y-axis of the motion simulator. At 6 milli-g, the motion simulator was tested at 0.10, 0.16, 0.25, 0.40, and 0.63 for both x- and y- axes. As the accuracy of the peak displacement measurements were rounded to the nearest 1 mm, the motion simulator was not tested at 6 milli-g, 1 Hz motion, which has a peak displacement of approximately 1.5 mm. Each motion condition comprised 10 cycles. The positive peak displacements of the 10 cycles of a motion condition were averaged to calculate a positive output peak displacement. Negative output displacements were calculated similarly.

Table 3.1 summarises the calibration results of all tested motion conditions. In general, differences between input and output peak displacements for both x- and y- axes were less than 3%. Correlation analyses suggested that the coefficients of determination between input and output peak displacements for both x- and y- axes were equal to one. As shown in Figure 3.7, nearly perfect positive correlations exist between input and output peak displacements for both x- and y- axes with a slope equalling one. Hence the motion simulator is able to accurately reproduce the tested motion conditions.

Table 3.1. A summary of calibration results of all tested motion conditions.

Axis	Frequency (Hz)	Peak acceleration = 30 milli-g			Frequency (Hz)	Peak acceleration = 6 milli-g		
		Peak displacement (mm)		Displacement distortion (%)		Peak displacement (mm)		Displacement distortion (%)
		Input	Output			Input	Output	
x-axis	1	7.0	7.0	0.00	--	--	--	--
	0.63	19.0	19.0	0.00	0.63	4.0	4.0	0.00
	0.4	47.0	47.0	-0.01	0.4	9.0	9.0	0.00
	0.25	119.0	119.0	0.00	0.25	24.0	23.8	-0.71
	0.16	291.0	291.7	0.23	0.16	58.0	58.2	0.28
	0.14	380.0	380.8	0.22	0.1	149.0	149.4	0.25
y-axis	1	7.0	7.0	0.00	--	--	--	--
	0.63	19.0	19.0	0.00	0.63	4.0	4.0	0.00
	0.4	47.0	47.5	1.06	0.4	9.0	9.0	0.00
	0.25	119.0	119.3	0.28	0.25	24.0	23.8	-1.04
	0.16	291.0	291.5	0.17	0.16	58.0	58.1	0.14
	0.1	745.0	746.3	0.17	0.1	149.0	149.3	0.17

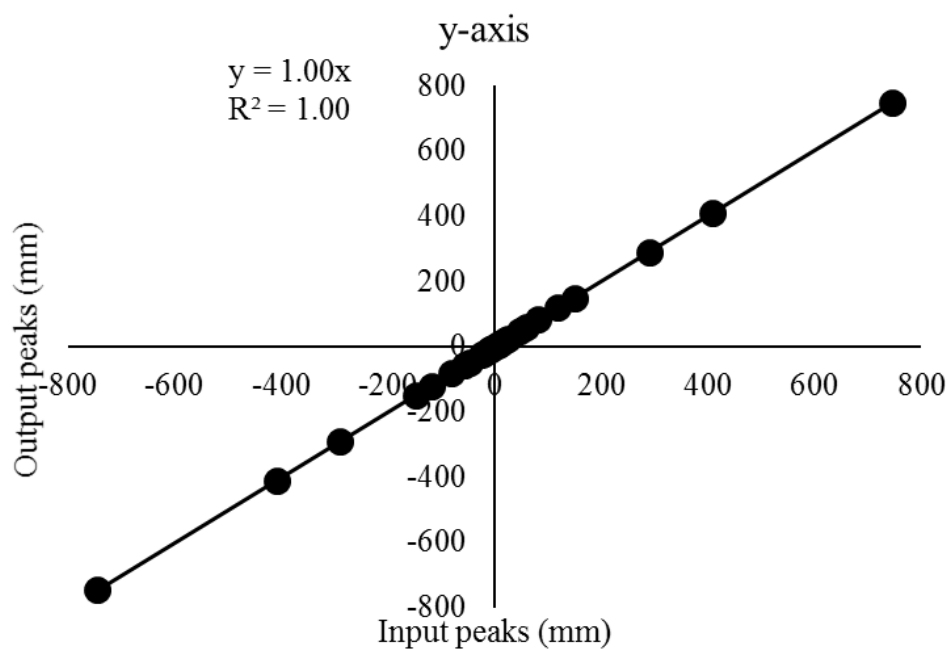
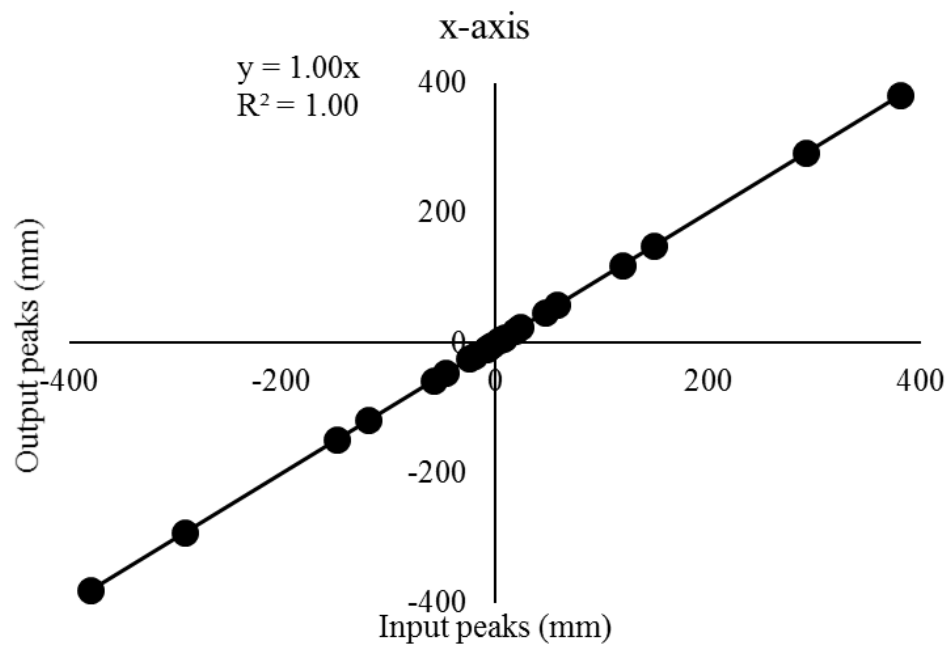


Figure 3.7. Correlations between input and output displacement peaks for x- and y-axes.

A pair of orthogonally aligned accelerometers was installed to measure acceleration time histories of the motion simulator. The setup of the accelerometers is shown in Figure 3.8. Acceleration time histories of 12 motion conditions along the y-axis at three acceleration magnitudes (8, 16, and 30 milli-g) and four frequencies (0.125, 0.25, 0.5, and 1 Hz) were measured to determine if there was any frequency distortion of the motion reproduced by the motion simulator. The acceleration time histories were recorded for a duration of 180 seconds at a sampling frequency of 100 Hz.

Figure 3.9 to Figure 3.12 compare the power spectral density functions of the input and output acceleration time histories of the 12 motion conditions. The spectra confirm that the input and output of the 12 motion conditions were nearly identical, indicating that frequency distortion of the motion reproduced by the motion simulator was negligible.

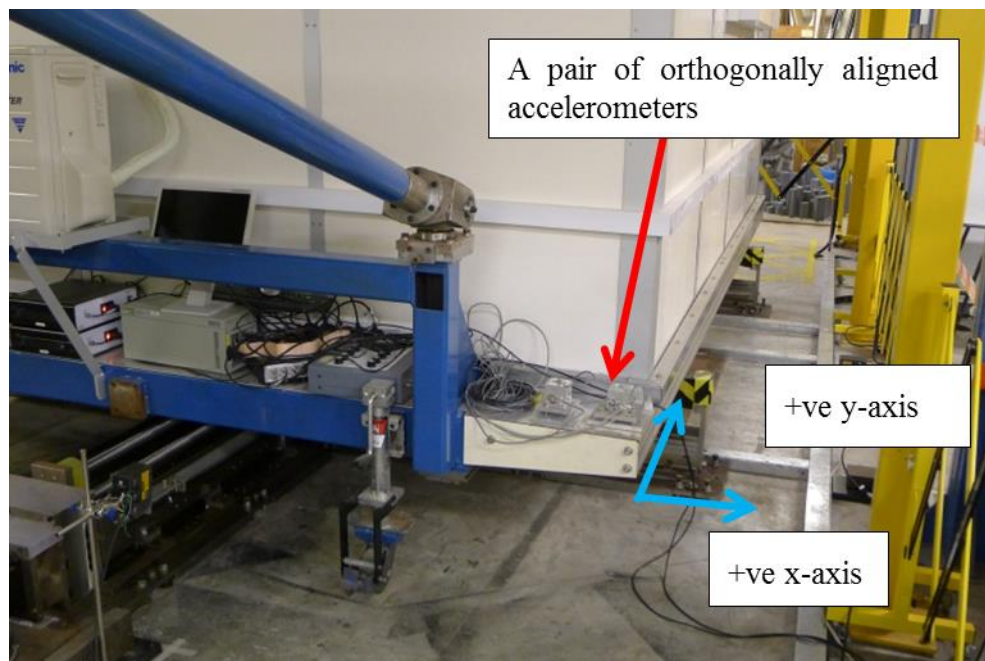


Figure 3.8. Experimental setup for motion simulator displacement measurements

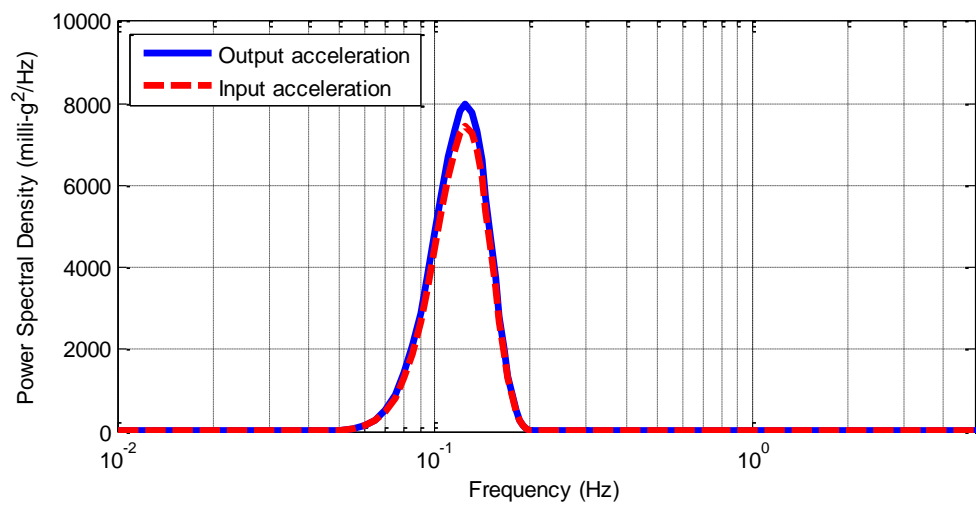
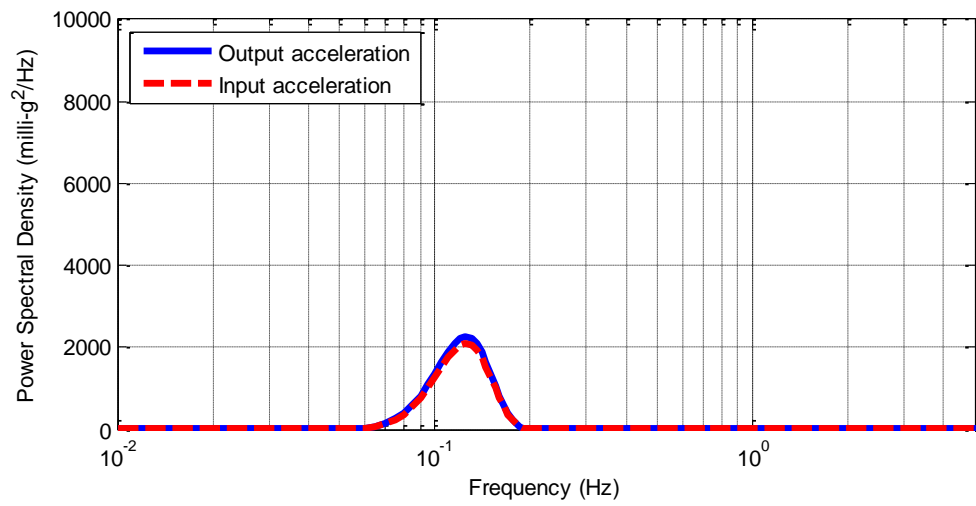
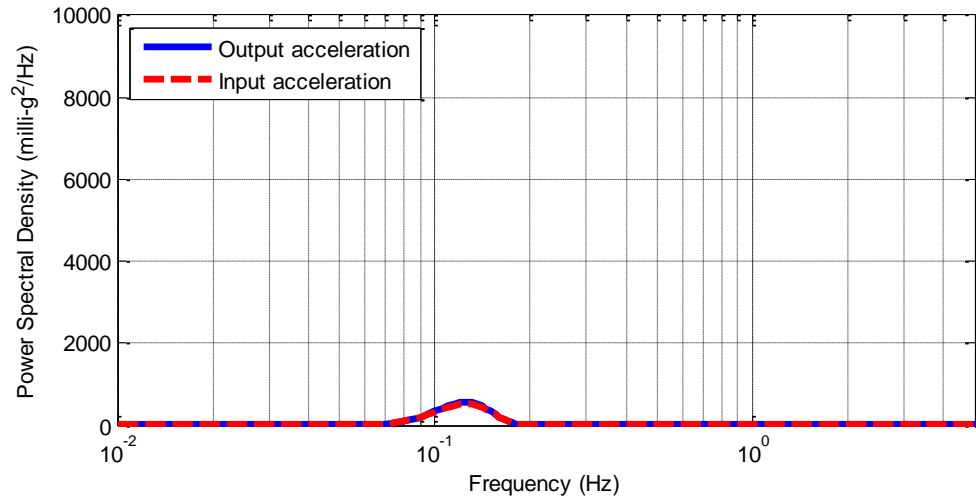


Figure 3.9. Power spectral density functions of input and output acceleration time histories at 0.125 Hz: Top) 8 milli-g; middle) 16 milli-g; and bottom) 30 milli-g.

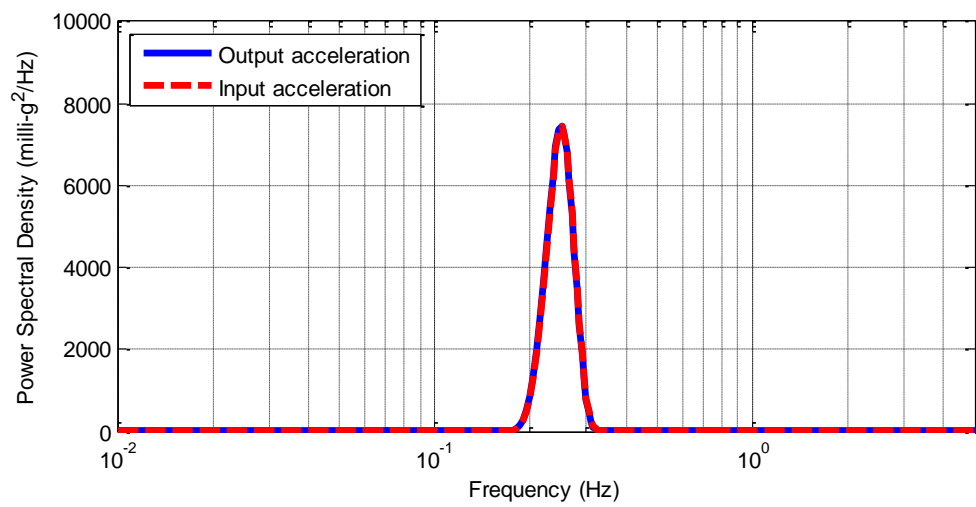
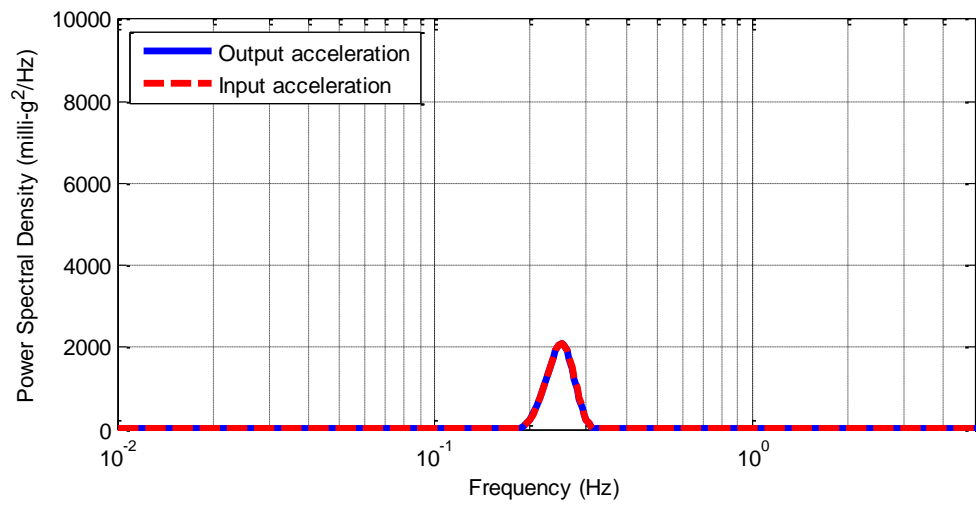
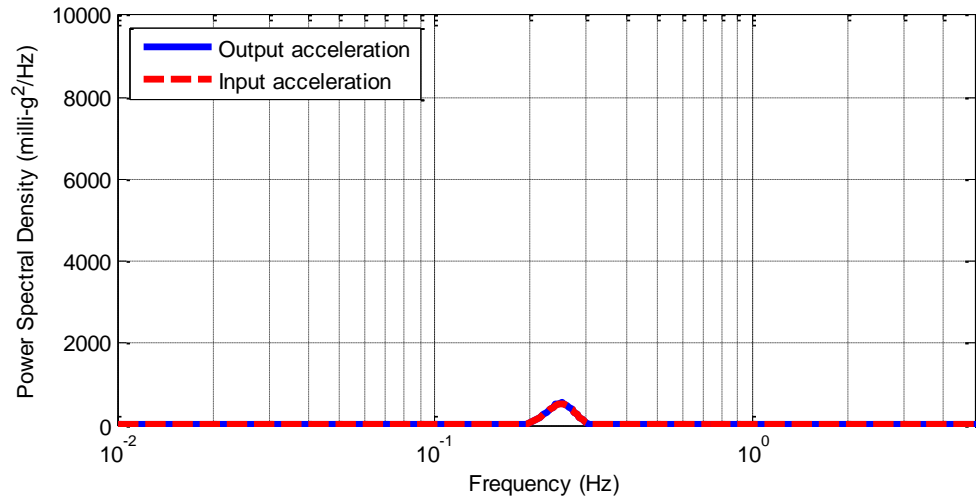


Figure 3.10. Power spectral density functions of input and output acceleration time histories at 0.25 Hz: Top) 8 milli-g; middle) 16 milli-g; and bottom) 30 milli-g.

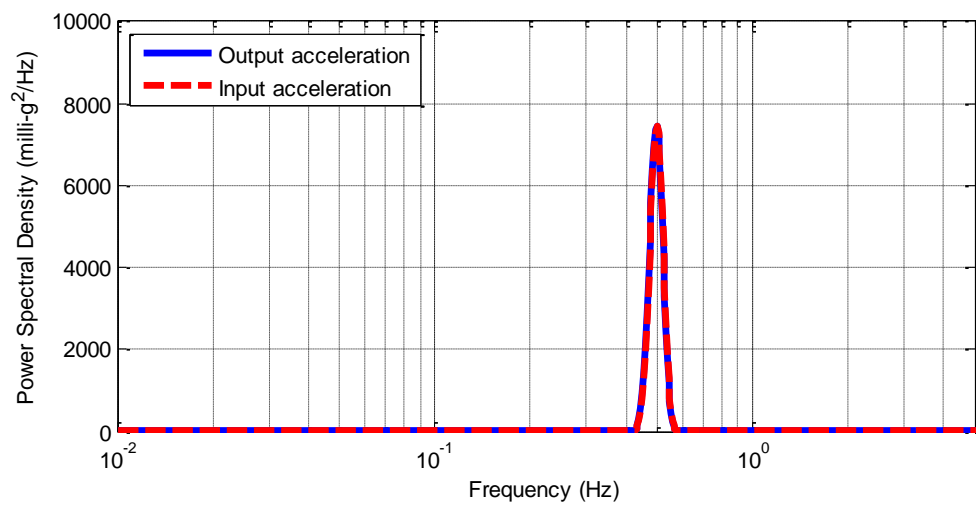
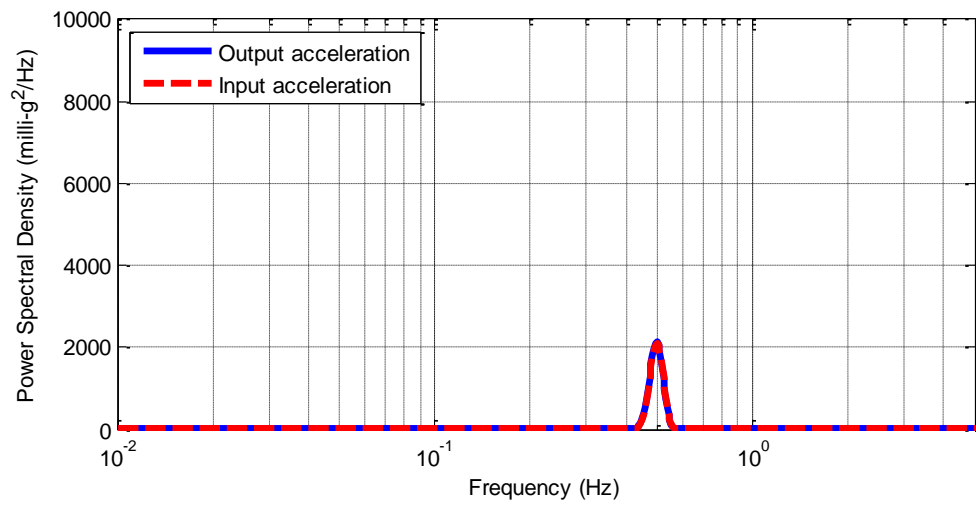
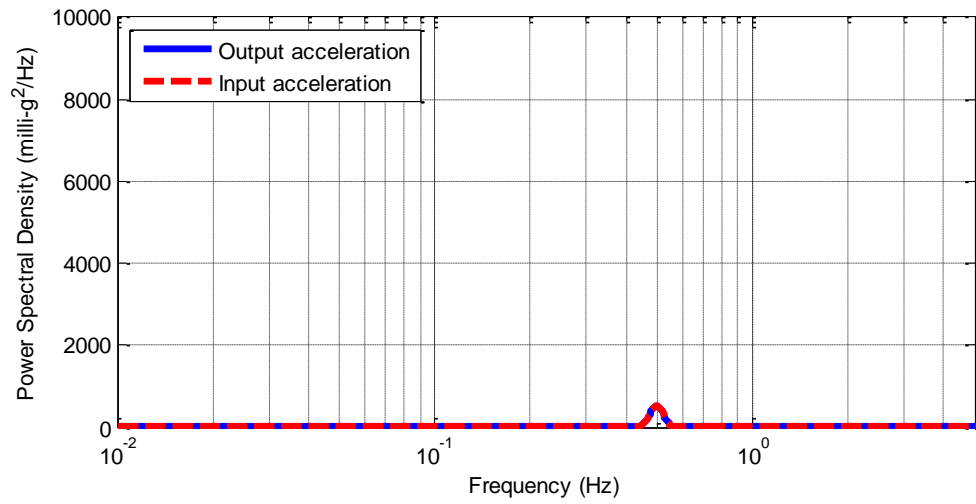


Figure 3.11. Power spectral density functions of input and output acceleration time histories at 0.5 Hz: Top) 8 milli-g; middle) 16 milli-g; and bottom) 30 milli-g.

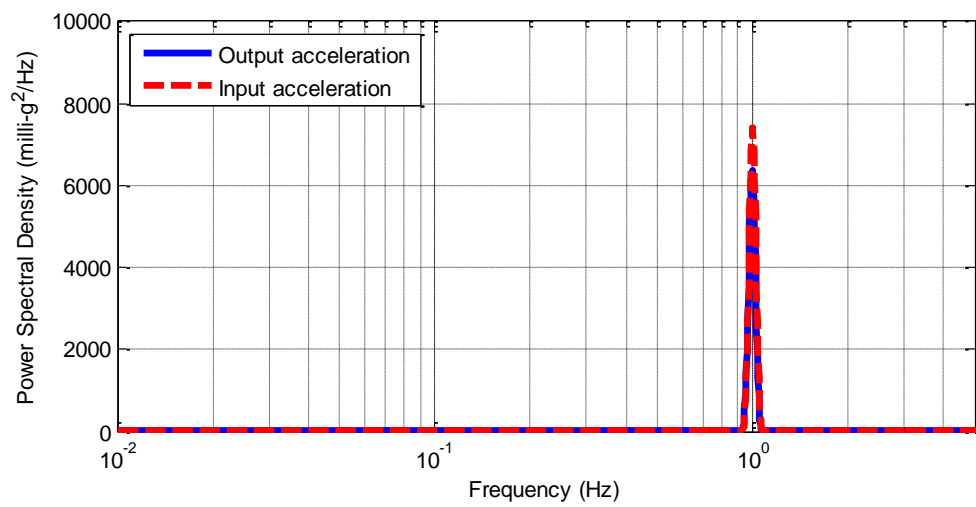
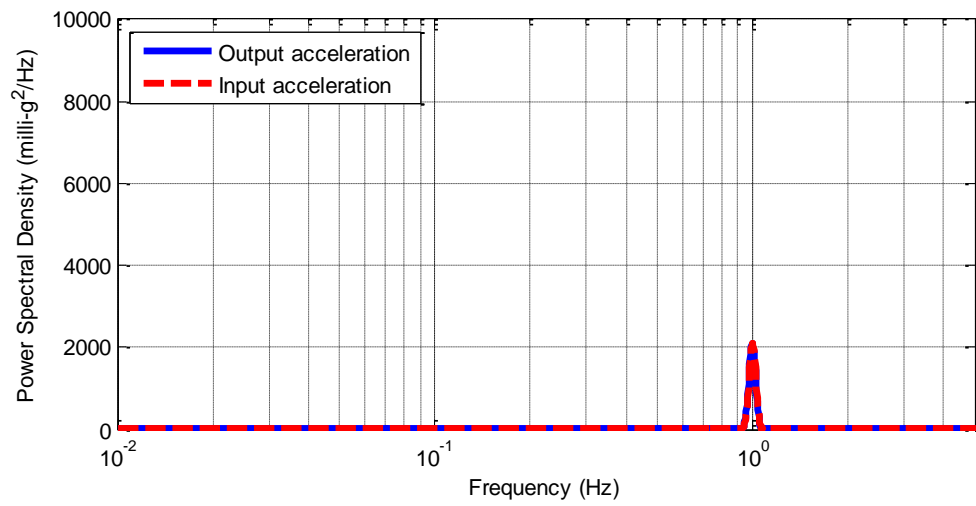
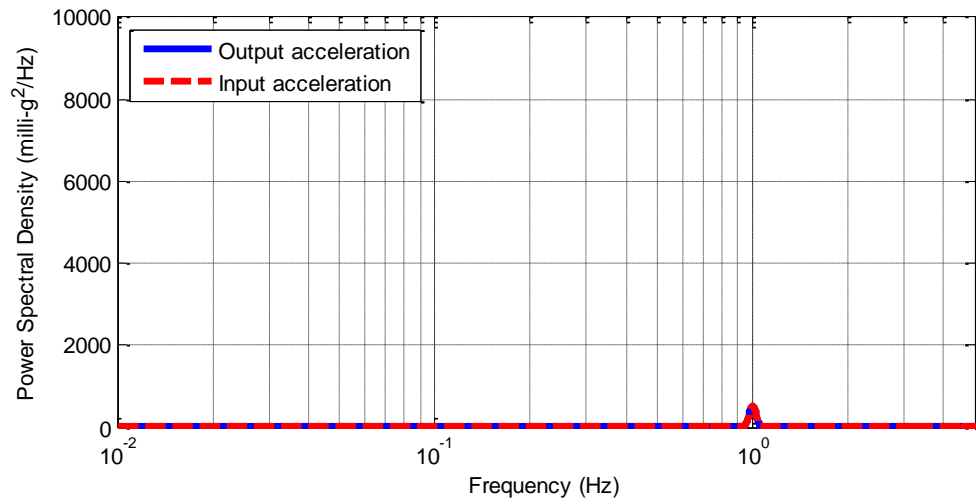


Figure 3.12. Power spectral density functions of input and output acceleration time histories at 1 Hz: Top) 8 milli-g; middle) 16 milli-g; and bottom) 30 milli-g.

3.4 Experiment protocol for measuring manual task performance, sopite syndrome severity, and EMG signals

3.4.1 Participants

In total, 44 participants were tested. Among the 44 participants, 40 completed the experiment and formed the main sample of this thesis, four felt sick and could not complete the experiment. For the rest of this thesis, unless specified, participants refers to the 40 individuals who completed the experiment. All were undergraduate students of HKUST and the group evenly represented genders with 20 males and 20 females, with a mean age of 21 ± 3 years. Participants were recruited by email invitation, gave their informed consent and were compensated 50 HKD per hour. The participants provided personal information, including age and gender using a general information form as shown in Appendix A.

The manual task performance of 20 participants (10 males; 10 females) was measured under fore-aft motion conditions and the performance of the other 20 participants (10 males; 10 females) was measured under lateral motion conditions. The results of the manual task performance measured under both fore-aft and lateral motion conditions are presented in Chapter 4.

The severity of motion sickness of the 44 participants was measured before and after exposure to motion. The motion sickness severities and its effects on manual task performance of the 40 participants who completed the experiment are presented in Chapter 5. The motion sickness severities and their effects on manual task performance of the four participants (1 male and 3 females under lateral motion conditions) who felt sick and asked to stop the experiment were not included in the main analyses, but are discussed separately in Chapter 5.

In studies on human balance, postural control in the fore-aft direction is the most commonly discussed (Winter, 1995) and body motion in the fore-aft direction is the most important for maintaining balance recovery (Hwang et al., 2009). Therefore, this thesis focuses on the effects of fore-aft, low-frequency, low-acceleration motion on the activation levels of the leg muscles involved in postural control in the fore-aft direction only. Activation level measurements of the soleus (SOL) and tibialis anterior (TA), the two muscles primarily involved in maintaining balance in the fore-aft direction, were carried out with the 20 participants who were tested under fore-aft motion conditions. The results of the muscle activation levels are presented in Chapter 6.

3.4.2 Continuous tracking task

Goto et al. (1990) measured performance degradation under low-frequency, low-acceleration motion conditions using a continuous manual task. They found that performance of the continuous manual task was degraded by 0.23 Hz circular motion at acceleration magnitudes of 4 milli-g or above. Burton et al. (2011), however, found that the effects of low-frequency, low-acceleration motion on a discrete manual task were not significant. Furthermore, McLeod and Griffin (1988) showed that effects of vertical translational motion on a continuous tracking task were more significant than in a discrete tracking task. It is therefore reasonable to believe that the effects of low-frequency, low-acceleration motion are likely to be more significant on continuous than discrete manual tasks.

A continuous tracking task (CTT) was used in this thesis as a paradigm to quantify the effects of low-frequency, low-acceleration motion on manual task performance. The CTT required participants to hold a laser pointer in their dominant hand, and aim a laser light dot as close as possible to the centre of a target mounted two metres in front of them and 1.3 meters above the floor. The target comprised three concentric circles, with radii of 20, 40 and 60 mm, as shown in Figure 3.13. Figure 3.14 shows a participant performing the CTT inside the motion simulator. The duration of the CTT was 64 seconds.

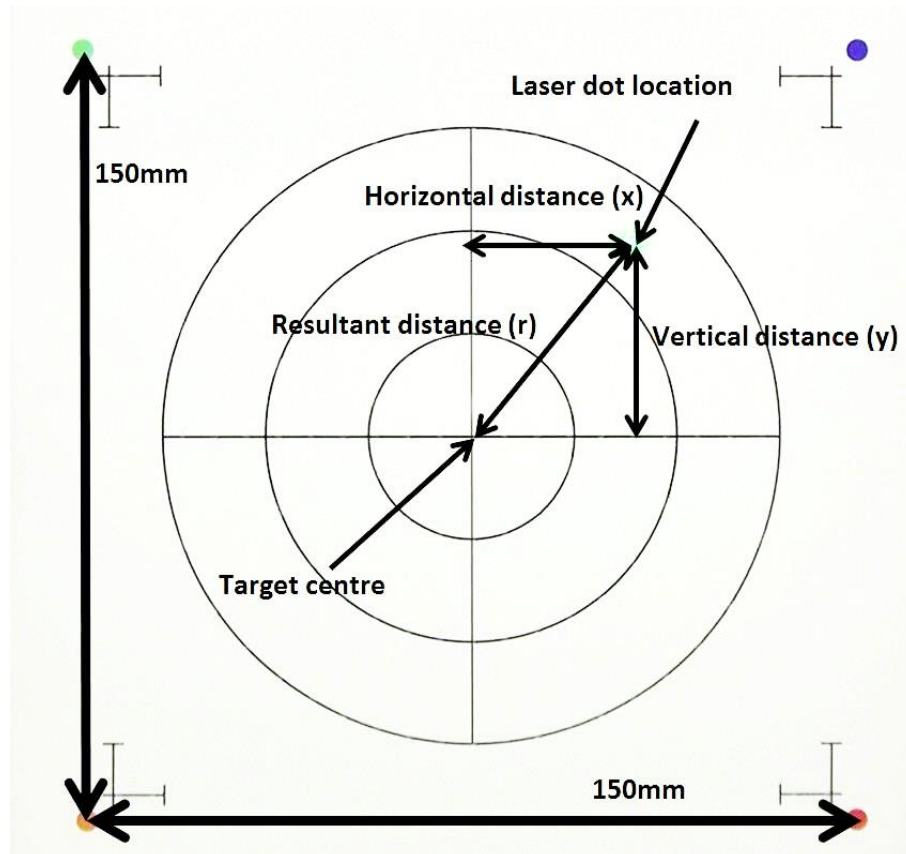


Figure 3.13. An illustration of the horizontal, vertical, and resultant distances between a laser light dot and target centre. The resultant distance was used as a measure for overall CTT performance evaluation.



Figure 3.14. A participant performing the CTT inside the motion simulator.

A digital video camera (Sony HDR-GW77VE), as shown in Figure 3.15, was installed behind the target to record the laser light dot movement. Videos were recorded at a sample rate of 50 Hz and a resolution of 1080p (1920x1080 pixels). A custom MATLAB algorithm was used to determine the horizontal (x) and vertical (y) distances of the laser light dot from the centre of the target. One pixel in the recorded video is approximately equal to 0.16 mm on the physical target.



Figure 3.15. The digital video camera (Sony HDR-GW77VE) used to record laser light dot movement.

Horizontal and vertical distances of the 64-second video were used to form a laser light dot locus. An example of this is shown in Figure 3.16. Laser light dot loci were inspected to check whether the horizontal and vertical distances were determined properly and check whether participants had directed the laser light dot outside the target.

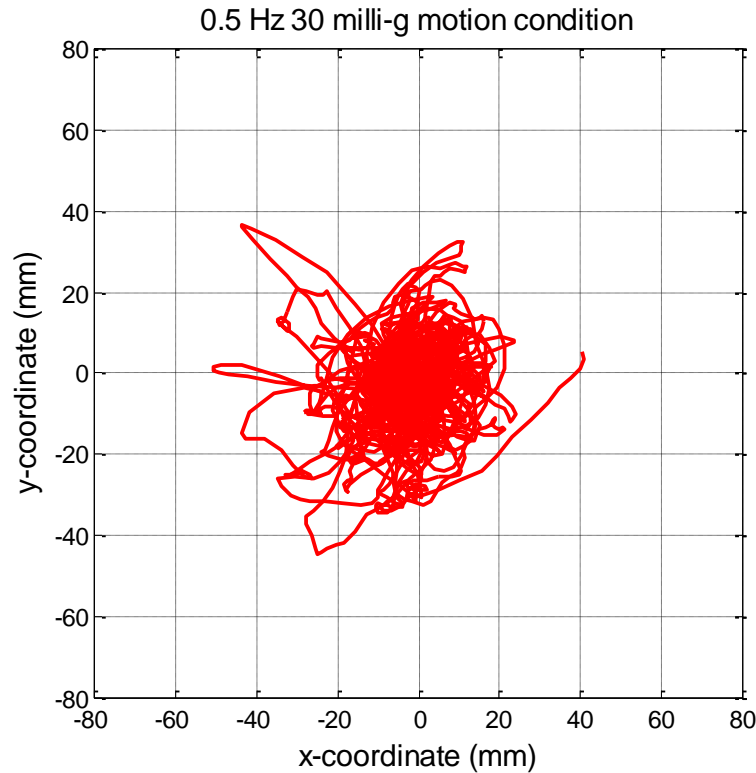


Figure 3.16. An x-y plot of a 64-second locus measured under a 0.5 Hz 30 milli-g fore-aft motion condition for a test participant.

3.4.3 Motion characteristics

Wind-induced forces and responses of a bluff body, such as buildings or other civil structures, can be resolved into two orthogonal directions based on either wind axes or body axes as shown in Figure 3.17. Because excitation mechanisms are more relevant to the mean wind direction than the geometry of the bluff body, the wind-induced forces and responses are generally defined based on the wind axes rather than the body axes (Melbourne, 1975). The wind-induced forces and responses that are parallel to the mean wind direction are alongwind and those perpendicular to the mean wind direction are crosswind as shown in Figure 3.17 (a).

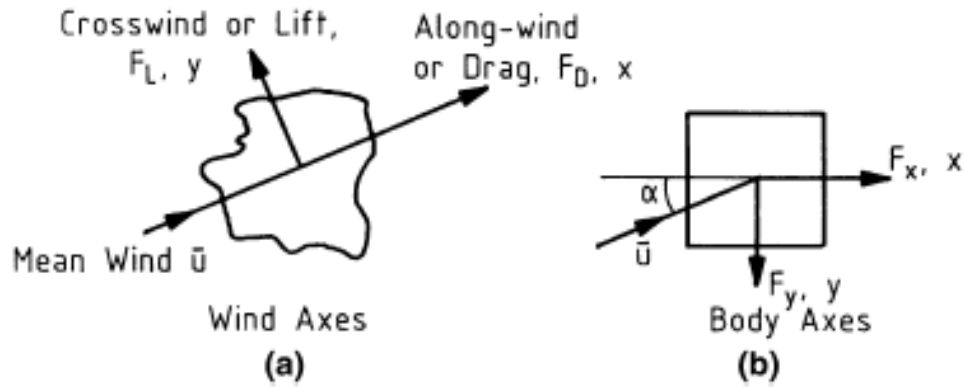


Figure 3.17. Wind-induced force and response components defined based on a) wind axes and b) body axes (reproduced from Figure 5.1 of Tamura and Kareem (2014)).

Wind-induced forces acting on a bluff body may be arisen from several mechanisms such as incidence turbulence of the atmospheric boundary layer, vortices shed by the bluff body itself and / or other bluff bodies adjacent to it, and the motion of the bluff body itself. The mechanisms do not always occur in isolation but are frequently superimposed, particularly in the crosswind direction (Melbourne, 1975). In general, the wind-induced force in the alongwind direction is dominated by turbulence buffeting. In contrast, the excitation mechanisms associated with the crosswind direction are complex. Melbourne (1975) identified the variables and mechanisms that are associated with the crosswind response of structures as shown in Figure 3.18.

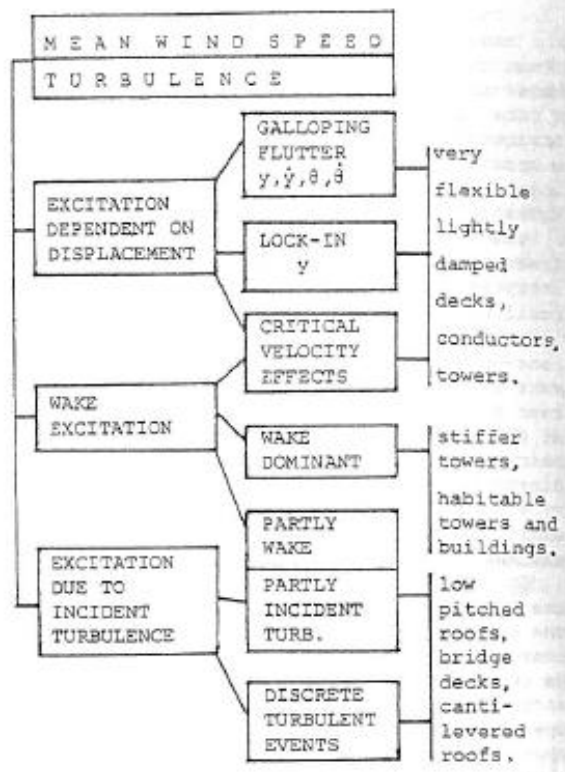


Figure 3.18. Variables and mechanisms that are associated with crosswind response of structures (reproduced from Figure 6 of Melbourne (1975)).

Waveforms of wind-induced building motion vary significantly depending on excitation mechanisms, such as alongwind turbulence buffeting and crosswind vortex shedding (e.g. Melbourne, 1975, 1977). Dynamic building motion is usually greater in the crosswind than alongwind condition, resulting in planar motion with an elongated elliptical envelope. The crosswind dynamic building motion is usually induced by regular vortices shed by the building at a narrow range of frequencies. Hence, the dynamic crosswind building motion is narrow-band (that is, the building moves in a narrow range of frequencies in the crosswind direction). Initially, the building responds to the excitation energy from the shed vortices to build up the crosswind building motion. After several motion cycles, the building reaches a crosswind building motion with similar amplitude sustained over a short period. Because buildings normally dissipate energy during motion, the amplitude of crosswind building motion also diminishes over time. Hence, the amplitude envelope of the crosswind building motion typically shows distinct beats or “bursts” containing multiple cycles of relatively similar amplitude.

In a short duration (of the order of 1 minute), narrow-band dynamic crosswind building motion can be very similar to sinusoidal motion (as shown in Figure 3.19, which shows examples of narrow-band alongwind, crosswind, and torsional building motion). Considering the relatively short duration (64 seconds) of the CTT in each condition, this study used sinusoidal motion to most closely represent the sustained component of real building motion to assess the capacity for building motion to disrupt manual task performance. Accelerations (8, 16, and 30 milli-g) and frequencies (0.125, 0.25, 0.5, and 1 Hz) of a sine wave were manipulated to represent the motion conditions likely to occur in wind-excited buildings (Campbell et al., 2005; Isyumov et al., 1988; Kim and Kanda, 2008).

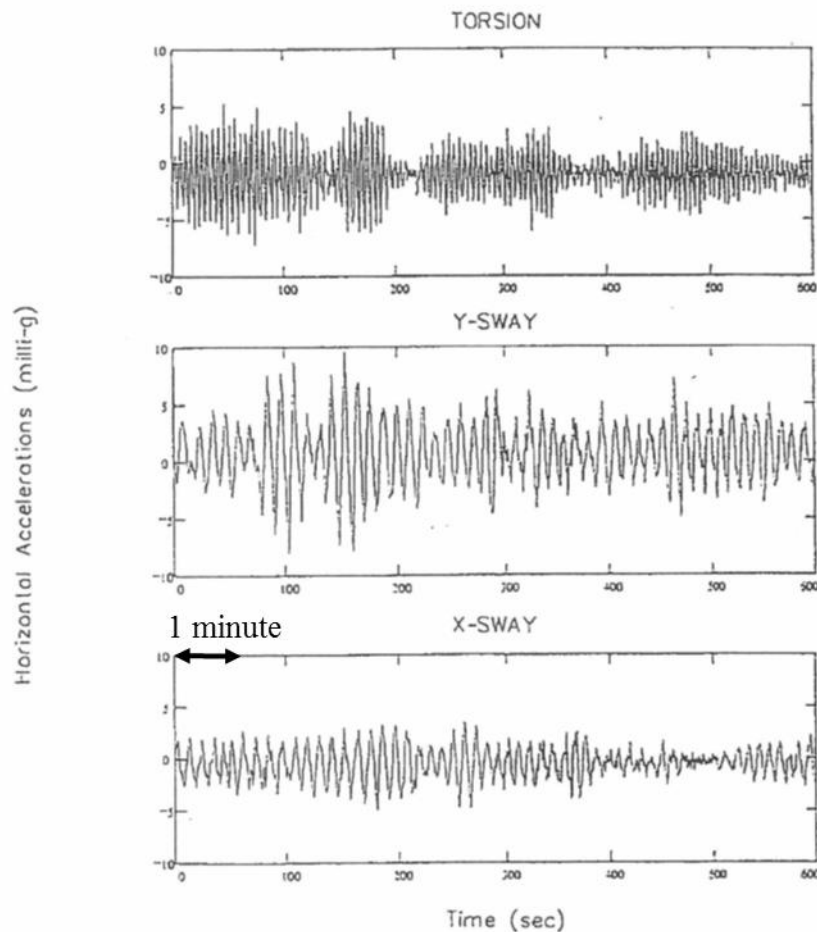


Figure 3.19. Examples of alongwind, crosswind, and torsional building motion (reproduced from Isyumov, 1995). Note the distinct beats or “bursts” containing multiple cycles of relatively similar amplitude.

3.4.4 Measures of motion sickness and sopite syndrome

A Motion Sickness Assessment Questionnaire (MSAQ) was used to measure motion sickness severity due to exposure to low-frequency, low-acceleration motion (Gianaros et al., 2001). The MSAQ measured self-reported motion sickness severity at a given time. To measure changes in motion sickness symptom severity due to exposure motion, participants completed the MSAQ before and after being exposed to all motion conditions.

The MSAQ is a 16-item scale, as shown in Appendix B. Participants rated each item on a 9-point scale, anchored at 1 = “Not at all” and 9 = “Severely”. The MSAQ overall motion sickness score is calculated using Equation 3.1. The maximum value, indicating the worst symptoms, is 100%.

Equation 3.1

$$\text{MSAQ overall motion sickness score} = (\text{sum of 16 items} / 144) \times 100\%$$

The MSAQ includes four subscales that measure the main components of motion sickness: gastrointestinal (G), central (C), peripheral (P), and sopite-related symptoms (S). Example items include: “I felt sick to my stomach.” (G), “I felt dizzy.” (C), “I felt clammy/cold sweat.” (P), “I felt drowsy.” (S). Each subscale score is the sum of the related items divided by the total possible score as a percentage, as shown in Equation 3.2.

Equation 3.2

MSAQ subscale score = (sum of subscale items / total possible score) x 100%

3.4.5 A computer-based data acquisition and analysis system for EMG measurement

A standard deviation of electromyographic signal (EMG_{SD}) quantifies the power of an electromyographic (EMG) signal and measures the activation levels or energy requirements of muscles (De Luca, 2002). Therefore, EMG_{SD} was used to measure the activation levels or energy requirements of the participants' SOL and TA, the two leg muscles involved in maintaining balance in the fore-aft direction. A computer-based data acquisition and analysis system was used to concurrently measure EMG signals of the SOL and TA. A schematic diagram of the computer-based data acquisition and analysis system is shown in Figure 3.20. . The system comprised a laptop computer, an analogue to digital data acquisition hardware, four high performance differential biological amplifiers, cables, and silver/silver chloride (Ag/AgCl) surface electrodes. The components of the data acquisition system are described below.

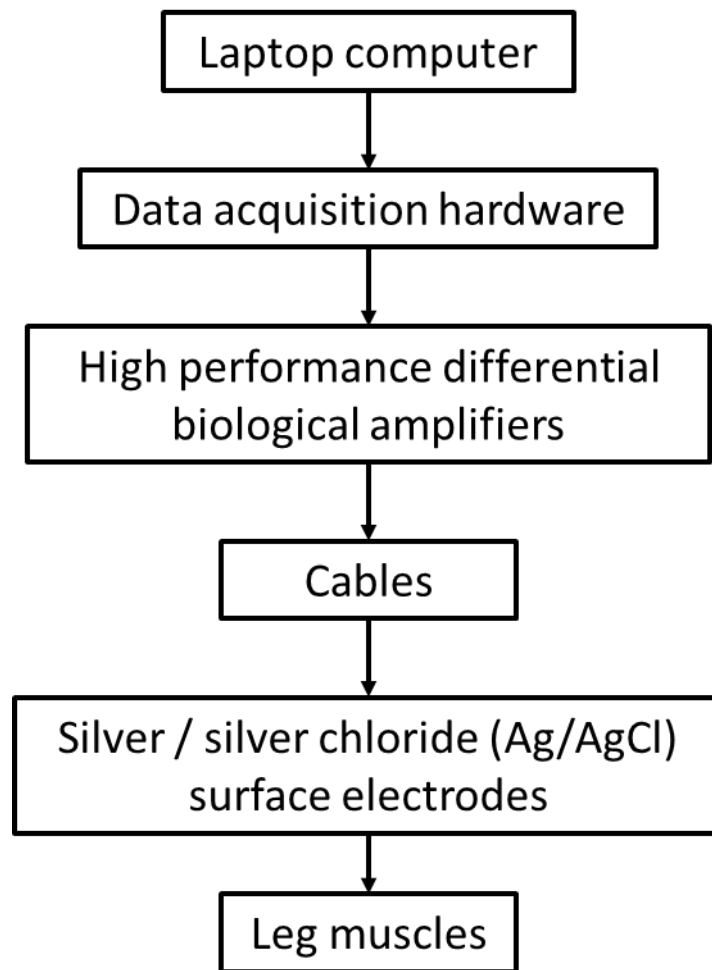


Figure 3.20. A schematic diagram of the computer-based data acquisition and analysis system.

3.4.5.1 Laptop computer

The laptop computer is a 15.4-inch MacBook Pro (Apple, California, USA). It is equipped with software, LabChart 7 Pro, (ADInstruments, Sydney, Australia) for controlling the data acquisition system, online monitoring on EMG signals, and offline data analyses. A view of LabChart 7 Pro running on the 15.4-inch MacBook Pro is shown in Figure 3.21.

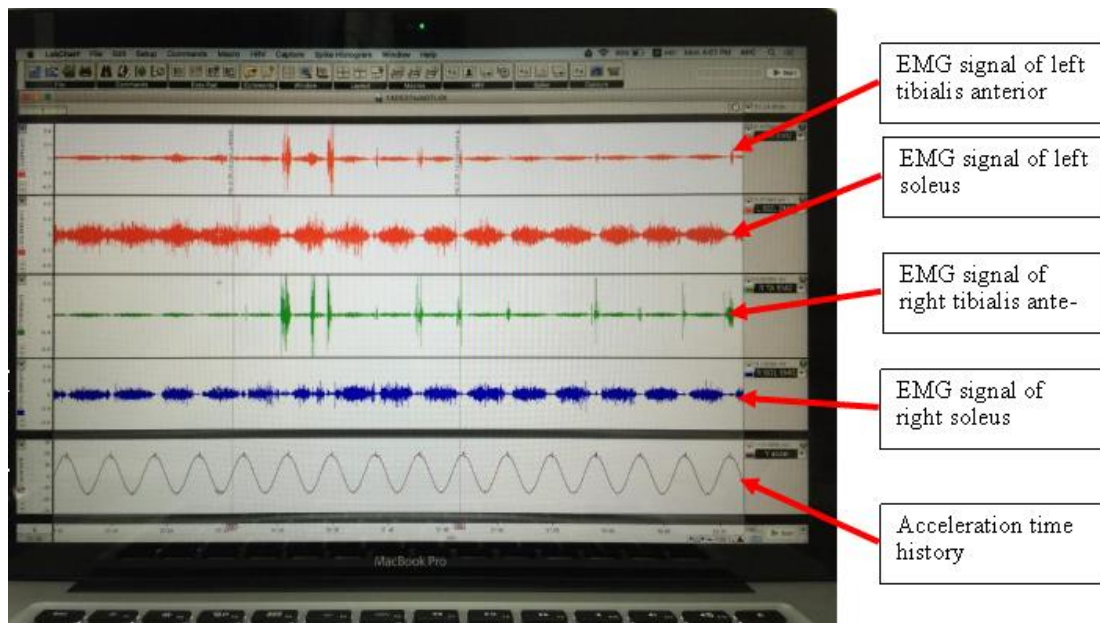


Figure 3.21. A view of LabChart 7 Pro installed on a 15.4-inch MacBook Pro.

3.4.5.2 Data acquisition hardware

The data acquisition hardware is a PowerLab 16/35 (ADInstruments, Sydney, Australia), as shown in Figure 3.22. The PowerLab 16/35 is 16-bit, with a maximum per channel sampling rate of 200,000 samples per second (S/s). Each channel has individual filters and noise reduction circuitry to minimize channel crosstalk and signal noise. It has 16 analogue input channels, 4 of which can be used in differential mode (“PowerLab | ADInstruments,” n.d.). The 4 differential mode analogue input channels are suitable for connections with 4 high performance differential biological amplifiers that will be described in the following section.



Figure 3.22. A PowerLab 16/35 of the computer-based data acquisition and analysis system (reproduced from “PowerLab | ADInstruments,” n.d.).

3.4.5.3 High performance differential biological amplifiers (Bio Amps)

The computer-based data acquisition and analysis system has four high performance differential biological amplifiers (Bio Amps, ADInstruments, Sydney, Australia), as shown in Figure 3.23. The Bio Amps are galvanically isolated and optimised for EMG recordings (“Bio Amps | ADInstruments,” n.d.).



Figure 3.23. A Bio Amp used for measuring EMG signals emanated from leg muscles (reproduced from “Bio Amps | ADInstruments,” n.d.).

3.4.5.4 Cables

The cables connecting a bio amp and surface electrodes comprise a Lead Shielded Bio Amp Cable and shielded lead wires (B/R/W, 3 pk), as shown in Figure 3.24 and Figure 3.25 respectively. The Lead Shielded Bio Amp Cable (MLA2340, ADInstruments, Sydney, Australia) is designed to connect a Bio Amp and shielded lead wires (B/R/W, 3 pk) (“Bio Amp Cables | ADInstruments,” n.d.). The shielded lead wires (B/R/W, 3 pk) (MLA2503, ADInstruments, Sydney, Australia) are 98 cm in length and comprise 4 mm 'snap-on' connectors that connect to disposable surface electrodes (“Biopotential Electrodes and Lead Wires | ADInstruments,” n.d.).



Figure 3.24. A Lead Shielded Bio Amp Cable (reproduced from “Bio Amp Cables | ADInstruments,” n.d.).



Figure 3.25. Shielded lead wires (B/R/W, 3 pk) (reproduced from “Biopotential Electrodes and Lead Wires | ADInstruments,” n.d.).

3.4.5.5 Surface electrode

The surface electrode is a 3M™ Red Dot™ Adult Solid Gel Electrode 2238 (3M™, USA), as shown in Figure 3.26. It is a circular electrode having an electrode diameter of six centimetres and sensor / solid gel diameter of two centimetres. The backing material of the electrode has high permeability allowing the skin to breathe and function normally. The electrode uses hypoallergenic adhesive and solid gel, ensuring minimal skin irritation (“3M™ Red Dot™ Adult Solid Gel Electrode 2238,” n.d.).

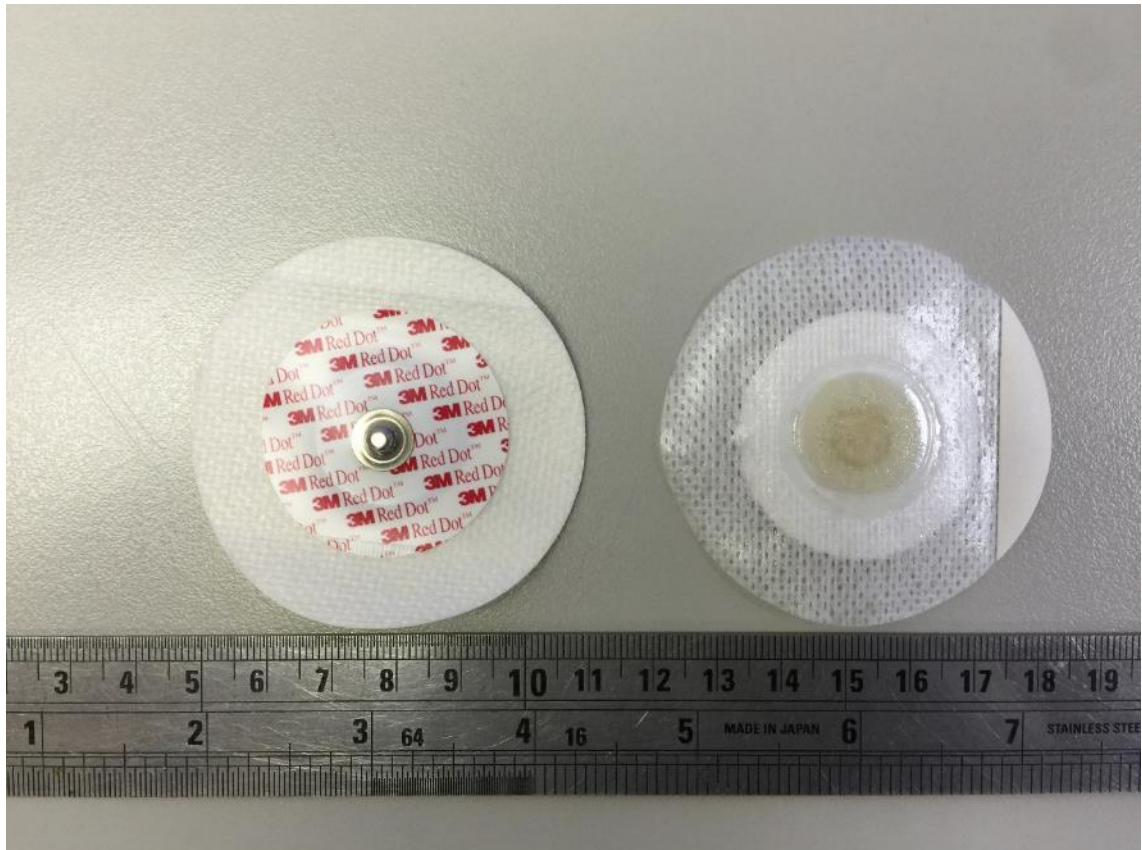


Figure 3.26. A 3MTM Red DotTM Adult Solid Gel Electrode 2238 (3MTM, USA).

3.4.6 Experimental procedure

This study used a three (Acceleration: 8, 16, 30 milli-g) x four (Frequency: 0.125, 0.25, 0.5, and 1 Hz) x two (Direction: fore-aft and lateral) mixed factorial design. Acceleration and frequency are within-subjects factors, while gender and motion direction are between-subjects factors (the effects of motion direction were investigated using two separate groups of participants). The dependent measures quantifying manual task performance are CTT performance is discussed in Chapter 4. Motion sickness severity and activation levels of leg muscles involved in maintaining balance in the fore-aft direction were also measured.

One participant was tested in each experimental session. Each participant was assigned at random to either fore-aft or lateral motion conditions. Participants completed a general information form and the Motion Sickness Assessment Questionnaire (MSAQ) and removed their shoes and socks prior to any experimental conditions or exposure to motion. Participants then practiced the CTT until they were familiar with the test procedure. During the CTT, participants maintained the same standing posture, with their legs 30 centimetres apart, holding a laser pointer in their dominant hand, with the other hand held straight down beside the trunk of body.

After finishing the practice session, the experimenter prepared the skin over the SOL and TA by using alcohol swabs to clean the skin surface and then attached surface electrodes onto the treated part of the skin over the SOL and TA. This ensured proper connection between skin surface and surface electrodes. Figure 3.27 demonstrates the locations of the surface electrodes. The red and white electrodes are respectively positive (+ve) and negative (-ve) detection electrodes, and the black electrodes are reference electrodes. The most suitable location for detection electrodes placement is in the direction of muscle fibres and near the point of greatest electrical activity. Therefore, the red positive detection electrodes were attached at the middle of the SOL and TA muscle fibres, and the white negative detection electrodes were attached on the end of the muscle fibres.

As the muscle belly expands during contraction, the mid-point and end-point of the SOL and TA are easily identifiable when the muscles are contracted. To identify locations of the mid-points and the end-points of the SOL and TA, participants contracted the SOL by flexing their feet downward toward the sole, as shown in Figure 3.28, and contracted the TA by flexing their feet in an upward direction, as shown in Figure 3.29. The positive electrode was attached at the middle of the SOL and TA muscle belly, and the negative electrodes over the tendon close to the end of the SOL and TA.

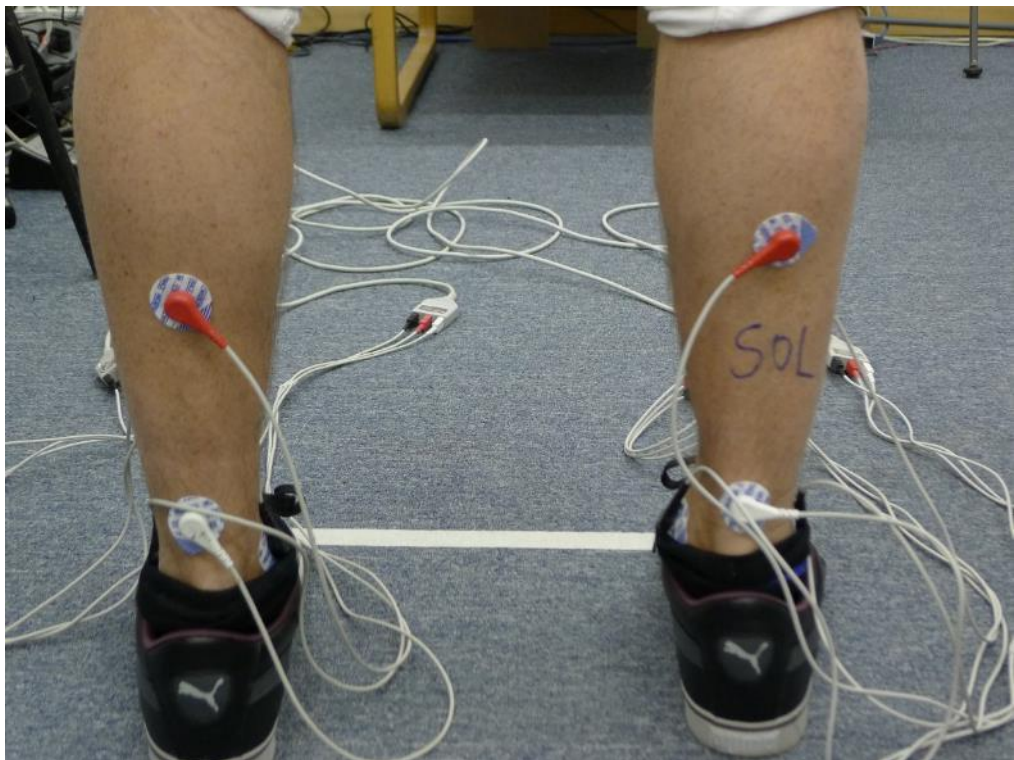
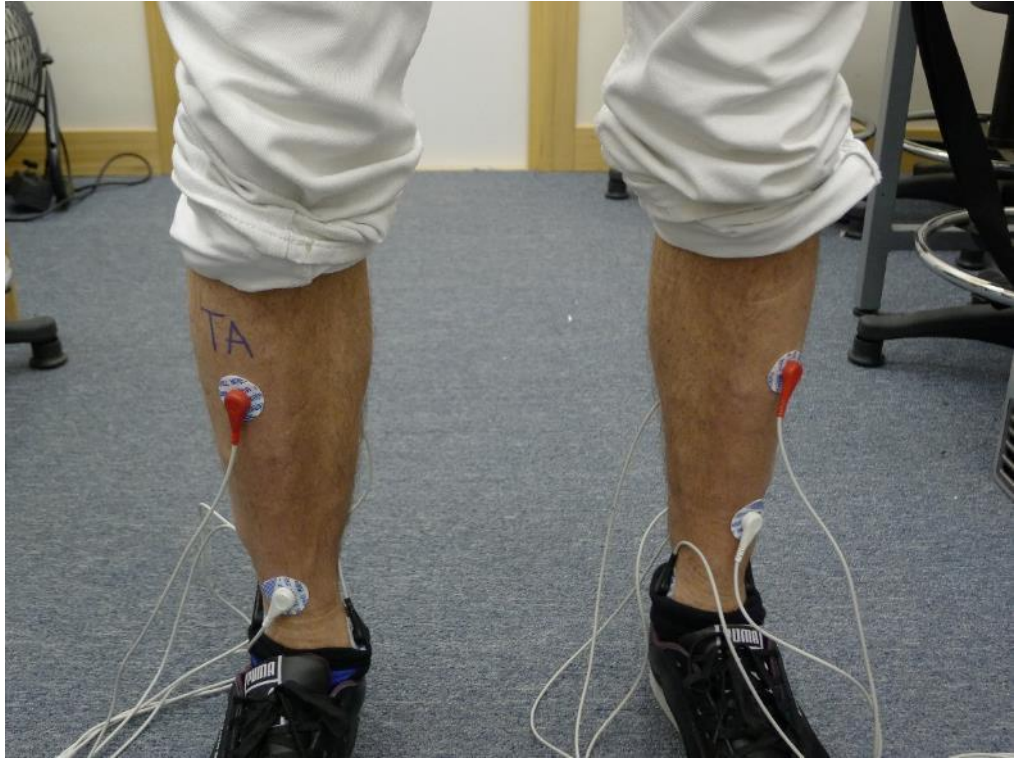


Figure 3.27. Locations of surface electrodes: Top) TA; Bottom) SOL. Red: White: Black are positive, negative and reference electrodes. Muscles and surrounding structure of TA and SOL can be referred to Figure 2.8.



Figure 3.28. A foot flexes downward toward the sole. The soleus (SOL) is contracted.



Figure 3.29. A foot flexes in an upward direction. The tibialis anterior (TA) is contracted.

Reference electrodes were connected to locations unaffected by the electrical signals emanating from the SOL and TA. In this study, the black reference electrodes were attached over medial malleolus and lateral malleolus respectively on outer and inner sides of an ankle, as shown in Figure 3.30.

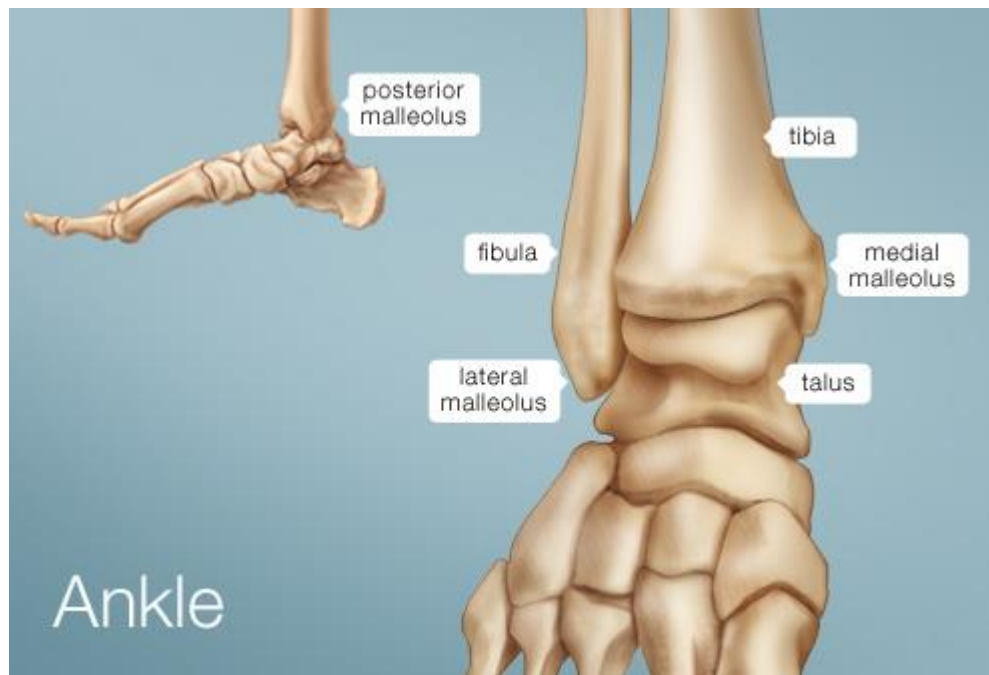


Figure 3.30. A figure showing locations of medial malleolus and lateral malleolus (reproduced from “picture-of-the-ankle,” 2014).

Participants stood with two postures to test whether the computer-based data acquisition and analysis system was properly connected to the leg muscles. The two postures were standing on heels and standing on toes, as shown in Figure 3.31 and Figure 3.32 respectively. A burst of EMG signal would appear in the online display channel of the TA when the participants were standing on their heels to contract the TA, and a burst of EMG signal would appear in the online display channel of the SOL when the participants were standing on their toes to contract the SOL.



Figure 3.31. A view of lower legs and feet while an individual stands on his heels.



Figure 3.32. A view of lower legs and feet while an individual stands on their toes.

Background noise contaminating EMG signals emanating from the leg muscles was unavoidable. A set of EMG signals regarded as background noises on the SOL and TA EMG signals were needed as reference for analyses. The background noise EMG signals comprised minimal EMG signals emanating from the SOL and TA. To measure the background noise EMG signals, participants sat on a chair and relaxed their SOL and TA for one minute. Under this sitting posture, the EMG signals during this rest period were assumed to be minimal because the leg muscles were relaxed and were not being used for maintaining balance.

After completing the setup for EMG measurements, participants stood up to attend an experimental session. Meanwhile, the experimenter commenced the SOL and TA EMG signal measurements at the beginning of each experimental session. The EMG signal measurements continued throughout the experimental session using the computer-based data acquisition and analysis system described in Section 3.4.5 .

An experimental session comprised 15 static and motion conditions. Each condition had two 64-second trials; one for performing the CTT, and the other without performing the CTT and standing at rest. Table 3.2 summarises all static and motion conditions of an experimental session. The experimental session always commenced and ended with a start-up condition and final static condition respectively, with the 12 motion conditions and an embedded static condition in the middle. Each participant experienced all motion conditions and the embedded static condition in a random order to balance any potential effects of motion sickness or other influencing factors such as fatigue and boredom over time.

Table 3.2. Static and motion conditions of an experimental session.

Condition	Order	Description	Frequency (Hz)	Acceleration (milli-g)
1	1	Start-up static	0	0
2	2-14 presented in random order	Motion	0.125	8
3		Motion	0.125	16
4		Motion	0.125	30
5		Motion	0.25	8
6		Motion	0.25	16
7		Motion	0.25	30
8		Motion	0.5	8
9		Motion	0.5	16
10		Motion	0.5	30
11		Motion	1	8
12		Motion	1	16
13		Motion	1	30
14		Embedded static	0	0
15	15	Final static	0	0

Participants experienced two 64-second trials during a condition; one for performing the CTT, and the other without performing the CTT and standing at rest, in an alternating order. A presentation order of all static and randomised motion conditions in an experimental session is shown in Table 3.3 as an example. During an experimental session, an experimenter stayed inside the motion simulator to facilitate progress by verbally instructing the participants to begin and end each trial. Meanwhile, the experimenter entered commentaries in the computer-based data acquisition and analysis system to mark the beginning and the end of each trial. The commentaries were used as markers to indicate the beginning and the end of EMG signals and for offline data analyses. A one minute rest break was provided between each condition.

Table 3.3. An example of presentation order of all static and motion conditions of an experimental session.

Condition	Trial	Performing CTT
Start-up static	1	Yes
	2	No
Motion condition 5	3	No
	4	Yes
Motion condition 10	5	Yes
	6	No
Motion condition 7	7	No
	8	Yes
Motion condition 3	9	Yes
	10	No
Embedded static	11	No
	12	Yes
Motion condition 9	13	Yes
	14	No
Motion condition 2	15	No
	16	Yes
Motion condition 11	17	Yes
	18	No
Motion condition 6	19	No
	20	Yes
Motion condition 13	21	Yes
	22	No
Motion condition 8	23	No
	24	Yes
Motion condition 12	25	Yes
	26	No
Motion condition 4	27	No
	28	Yes
Final static	29	Yes
	30	No

An experimental session ended after presenting all static and motion conditions. Participants then stood on their heels and stood on toes, as shown in Figure 3.31 and Figure 3.32 respectively, to confirm the computer-based data acquisition and analysis system was still properly connected to the leg muscles at the end of the measurement. This ensured the SOL and TA EMG signals were correctly recorded and collected. After the checking procedure, the experimenter detached the surface electrodes from participant's skin surface. Finally, participants completed the MSAQ again to record their motion sickness severity.

3.5 Concluding remarks

This chapter has presented a protocol for investigating the effects of low-frequency, low-acceleration motion and sopite syndrome on manual task performance. The protocol used a continuous tracking task as a paradigm to quantify the effects of motion on manual task performance. The sopite syndrome severity of participants was measured using a Motion Sickness Assessment Questionnaire (MSAQ). In addition, the protocol aimed to reveal the effects of motion and sopite syndrome, from a physiological perspective, on manual task performance and demonstrate whether compensatory action was carried out by participants under low-frequency, low-acceleration motion conditions by measuring the activation levels of leg muscles primarily involved in maintaining balance in the fore-aft direction. The purpose-built motion simulator at the Hong Kong University of Science and Technology (HKUST) was calibrated. Results of the calibration showed that the motion simulator can accurately reproduce the low-frequency, low-acceleration motion used in the protocol.

CHAPTER 4

EFFECTS OF LOW-FREQUENCY, LOW-ACCELERATION MOTION ON PERFORMANCE OF A CONTINUOUS TRACKING TASK

4.1 Introduction

An appropriate design of a habitable building might thoroughly consider effects of wind-induced building motion on human responses such as perception to motion, task performance, and well-being. However, few studies have investigated the effects of wind-induced building motion on manual task performance (for example Burton et al, 2011; Goto et al., 1990; Irwin and Goto, 1984). Further, these studies have produced conflicting results. Irwin and Goto (1984) and Goto et al. (1990) investigated the effect of motion on manual task performance in motion simulators, requiring participants to conduct basic tasks such as pouring water, tracing line patterns, and threading a needle. Both studies found that motion impaired manual task performance. However, these studies only investigated a narrow range of accelerations and frequencies and did not attempt to explain the mechanisms for the degradation in performance.

Burton et al. (2011) tested the effects of a range of bi-directional, narrow-band random accelerations on aiming accuracy in a video game. The study found no significant effect of motion on task performance accuracy or task time-to-completion relative to a control condition (no motion). However, 50% of participants reported difficulty balancing during motion. Burton et al. (2011) concluded that participants were able to compensate for motion and to maintain accuracy comparable to static conditions even at peak accelerations as high as 30 milli-g, and that task performance was not likely to be affected within a realistic range of building accelerations.

Wertheim (1998) argued that motion can reduce performance due to motion sickness-induced reductions in motivation, fatigue caused by increased energy requirements, and/or balance impairments. Motion-induced body movement can also affect performance, including interference with oculomotor control and/or motor skills (for example McLeod and Griffin, 1988, 1995; Yu et al., 2010). However, most studies were conducted under real or simulated transportation environments, particularly ships. The motion experienced in transportation environments is different from wind-excited buildings. Transportation motion is usually three-dimensional, including substantial vertical, pitch, and roll components. Further, the motion associated with modern forms of transport is usually at accelerations and frequencies far in excess of those that occur in wind-induced building motion. Therefore, the results of these studies may not be directly applicable to building designs.

Previous studies showed that gender and motion direction can influence human responses under low-frequency, low-acceleration motion conditions. Kanda et al. (1988) for example suggested that females were more sensitive to motion than males. In addition, the perception thresholds in the lateral direction were slightly lower than in the fore-aft direction. Goto et al. (1990) attempted to investigate the effects of motion on manual task performance. However, Goto et al. (1990) recruited only females to participate in the study. Furthermore, no study has investigated the effects of motion direction on manual task performance. The effects of gender and motion direction on manual task performance are yet to be fully understood.

A comprehensive understanding of motion effects on manual task performance in wind-excited buildings is important to optimise the design of habitable buildings. To address the deficiencies in this information, a series of motion simulator studies was conducted to investigate the effects of motion on manual task performance. The study aims to:

- i) determine whether low-frequency, low-acceleration motion degrades manual task performance in the range of frequency and acceleration comparable to wind-induced building motion and, if it does,
- ii) explore how manual task performance is degraded as a function of motion frequency and acceleration,

- iii) determine the relative contributions of frequency and acceleration in this degradation,
- iv) explore any effects of gender,
- v) determine the effect of motion direction on manual task performance, and
- vi) explore the implications of manual task performance degradation on the criteria and recommendations for the evaluation of occupant responses to wind-induced building motion.

4.2 Method

The motion simulator study used a continuous tracking task (CTT) as a paradigm to investigate the effects of motion on manual task performance. The CTT required participants to hold a laser pointer and aim a laser light dot as close as possible to the centre. Twenty participants were tested under fore-aft sinusoidal motion conditions and another 20 were tested under lateral conditions. Three acceleration magnitudes (8, 16, and 30 milli-g) and four frequencies (0.125, 0.25, 0.5, and 1 Hz) were used to produce 12 motion conditions. These acceleration and frequency ranges are comparable to those likely to occur in buildings undergoing wind-induced motion. Details of the participants, continuous tracking task, and experimental procedure have been presented in Chapter 3.

4.3 Analysis

4.3.1 Dependent measures

Resultant distance (r) is the main dependent measure for CTT performance. It is a combined deviation of a laser dot from the centre of a target. It was calculated using horizontal (x) and vertical (y) distances, as shown in Equation 4.1. Figure 4.1 shows an example of time histories of horizontal and vertical deviations and the corresponding resultant distance of a laser light dot locus. Mean, standard deviation, and maximum of the resultant distances (\bar{r} , σ_r , and \hat{r}) respectively represent average accuracy, fluctuation, and maximum excursion of the CTT. Increases of \bar{r} , σ_r , and \hat{r} respectively represent degradations of average, fluctuation, and maximum excursion of CTT performance.

Equation 4.1

$$\text{Resultant distance (r)} = \sqrt{x^2 + y^2}$$

where

x and y are respectively the horizontal and vertical distances from the centre of the target.

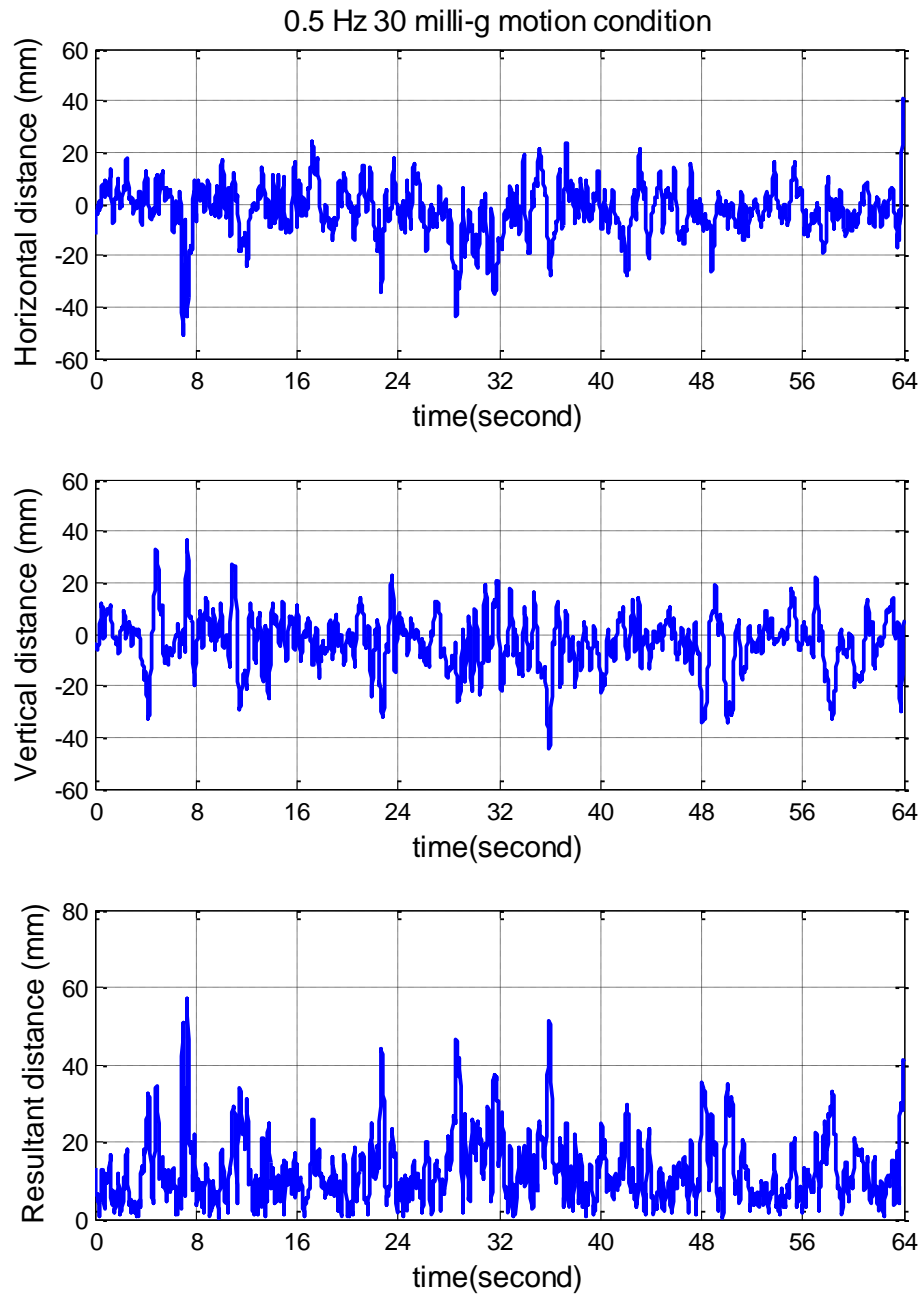


Figure 4.1. Time histories of horizontal and vertical deviation and the corresponding resultant distance of a laser light dot locus.

4.3.1.1 Mean resultant distance

Mean resultant distance (\bar{r}), a measure of average accuracy of the CTT, was calculated based on Equation 4.2.

Equation 4.2

$$\text{Mean resultant distance } (\bar{r}) = \frac{1}{N} \sum_{i=1}^N r_i$$

where

N is the sample size used for calculating mean resultant distance. For a 64-second CTT trial sampled at 50 Hz, the number of data used for the calculation was 3200.

4.3.1.2 Standard deviation resultant distance

Standard deviation of the resultant distance (σ_r), a measure of the variance in CTT, was calculated based on Equation 4.3.

Equation 4.3

$$\text{Standard deviation resultant distance } (\sigma_r) = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (r_i - \bar{r})^2}$$

where

N is the sample size used for calculating standard deviation resultant distance.

For a 64-second CTT trial sampled at 50 Hz, the number of data points used for the calculation was 3200.

4.3.1.3 Maximum resultant distance

Maximum resultant distance (\hat{r}) for each 64-second CTT trial was determined to evaluate the maximum excursion of a laser light dot due to motion effects. In a given trial, participants may carry out unusual actions, such as flicking their arms that hold the laser pointer. These unusual actions may result in a biased \hat{r} . In order to prevent a biased value stemming from any unusual action, the \hat{r} was determined indirectly. A 64-second time history was truncated into eight segments of equal duration. The duration of each segment is eight seconds, which is the least common multiple of the periods (i.e. 1/frequency) of the motion used in this study. Each segment hence comprises one or multiple intact motion cycle(s). This analysis ensures each eight-second segment is adequately long to capture r influenced by at least one intact motion cycle. An eight-second segment, for instance, comprises one intact cycle of a 0.125 Hz motion (period = eight seconds) and four intact cycles of a 0.5 Hz motion (period = two seconds), as shown in Figure 4.2. A maximum value ($\hat{r}_{8\text{-second}}$) was determined for each eight-second segment, as shown by the red circles in Figure 4.2. A maximum resultant distance (\hat{r}) was finally determined by averaging $\hat{r}_{8\text{-second}}$ of all segments, as shown in Equation 4.4.

Equation 4.4

$$\text{Maximum resultant distance } (\hat{r}) = \left(\sum_{i=1}^{i=8} \hat{r}_{8\text{-second},i} \right) / 8$$

where

$\hat{r}_{8\text{-second},i}$ is the maximum resultant distance of the i^{th} segment; and
 i is segment numbers ranging from one to eight for a 64-second sample.

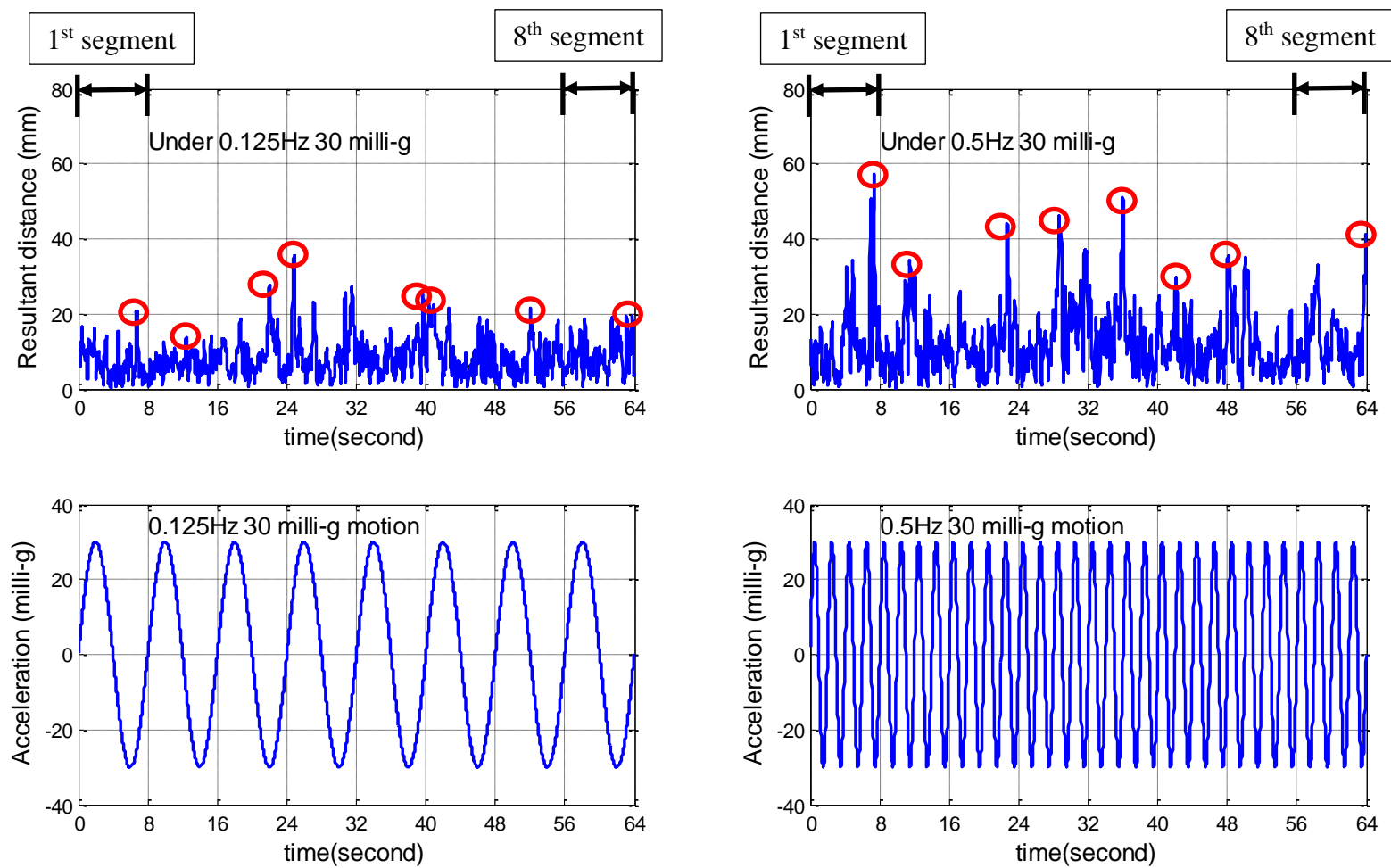


Figure 4.2. Truncations of resultant distance time history measured under 0.125 and 0.5 Hz motion conditions.

4.3.2 Exploratory data analysis

Prior to the detailed analyses, the mean, standard deviation, and maximum resultant distances (\bar{r} , σ_r , and \hat{r}) for all participants were inspected by using three-dimensional surface plots and box plots.

4.3.2.1 Three-dimensional surface plot

Three-dimensional surface plots were used to illustrate how \bar{r} , σ_r , and \hat{r} vary across frequency and acceleration. For example, a three-dimensional surface plot of the mean resultant distance (\bar{r}) demonstrated average magnitudes of \bar{r} for all participants under both fore-aft and lateral motion conditions for the 12 tested motion conditions. Values between tested frequencies and accelerations were linearly interpolated. Three-dimensional surface plots of σ_r and \hat{r} were plotted similarly.

4.3.2.2 Box plot

Dispersion, skewness, and outliers of \bar{r} , σ_r , and \hat{r} were visually inspected using box plots. A box plot is a graphical representation that comprises a box that shows the median, 25th and 75th percentiles data points, and whiskers that show maximum and minimum data points not considered as outliers. An interquartile range equals the difference between the 25th and 75th percentiles. The interquartile range is demonstrated by the length of a box and is used to define an outlier - a data point greater than the 75th percentile data value plus k times of the interquartile range, or smaller than the 25th percentile data value minus k times of the interquartile range. Outliers are shown individually in a box plot. The current study used a k value equals to 1.5, which correspond to 99.3% coverage if the data are normally distributed.

Mean resultant distance (\bar{r}) values of all participants were used for a box plot. The \bar{r} values were grouped by condition. For instance, all \bar{r} values measured under both fore-aft and lateral 0.125 Hz 8 milli-g conditions were plotted in one box while those \bar{r} values measured under both fore-aft and lateral 0.125 Hz 16 milli-g conditions were plotted in another box. σ_r and \hat{r} were plotted similarly.

4.3.3 Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows (Version 21.0) (IBM Corp., 2012). In general, effects are significant if the *p-value* < 0.05. *p-value* is the probability of incorrectly rejecting a true null hypothesis; a *p-value* of 0.05 means there is a five percent chance to reject the null hypothesis while in fact it is true.

The analysis further examined effect sizes of frequency and acceleration on CTT performance, \bar{r} , σ_r , and \hat{r} . Cohen's *d*, as shown in Equation 4.5, was used as a measure of effect size (Cohen, 1988). It provides a standardised measure of the magnitude of a difference between two groups, as a proportion of the pooled standard deviation. An effect size of 0.2, 0.5 and 0.8 or greater is considered small, moderate, and large respectively (Cohen, 1988).

Equation 4.5

$$\text{Cohen's } d = (M_1 - M_2) / \sigma_{\text{pooled}}$$

where

M_1 and M_2 are the mean of groups 1 and 2 respectively; and σ_{pooled} is the pooled standard deviation, defined as Equation 4.6.

Equation 4.6

$$\sigma_{\text{pooled}} = \sqrt{\frac{(n_1 - 1) \sigma_1^2 + (n_2 - 1) \sigma_2^2}{n_1 + n_2 - 2}}$$

where

n_1 and n_2 are the sample size of groups 1 and 2 respectively; and σ_1 and σ_2 are the squared standard deviations of groups 1 and 2.

In this study, the sample sizes of groups 1 and 2 were equal. Therefore, the pooled standard deviation can be calculated using Equation 4.7.

Equation 4.7

$$\sigma_{\text{pooled}} = \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}$$

4.3.3.1 Effects of motion

Effects of motion were demonstrated by comparing CTT performance, \bar{r} , σ_r , and \hat{r} , measured at 8 milli-g against embedded conditions. CTT performance measured at 8 milli-g, rather than 16 and 30 milli-g, were used for comparisons because 8 milli-g is the lowest acceleration tested in the current study and a peak acceleration magnitude of 8 milli-g can be considered to be satisfactory for office environments for frequencies ranging from 0.06 Hz to 0.5 Hz (International Organization for Standardization, 2007). The embedded static condition was designed to control for any potential effects of fatigue, boredom, or any other related natural causes over time. Therefore, CTT performance measured under the embedded static condition was used as a baseline for the comparisons. Paired-sample t -tests were used. \bar{r} , σ_r , and \hat{r} measured under the four 8 milli-g conditions (at 0.125, 0.25, 0.5, and 1 Hz) were combined as a sample and that of the embedded static condition, repeated four times, as another sample.

4.3.3.2 Effects of acceleration and frequency

Two-way repeated-measures Analysis of Variances (ANOVAs) were primarily used to investigate any effects of frequency and acceleration. The within-subjects factors were frequency and acceleration. CTT performance, \bar{r} , σ_r , and \hat{r} , are the dependent measures.

4.3.3.3 Effects of gender and motion direction

Mixed-design three-way ANOVAs with two within-subjects factors and one between-subjects factor were used to investigate the potential effects of gender and direction of motion. The two within-subjects factors were frequency and acceleration. The between-subjects factor is either gender or motion direction. CTT performance, \bar{r} , σ_r , and \hat{r} , were the dependent measures.

4.3.3.4 Difference between static conditions

Fatigue, boredom, or any other related natural causes over time may affect CTT performance. In the experiment, participants performed the CTT under start-up, embedded, and final static conditions. If the effects of fatigue, boredom, or any other related natural causes over time are significant, CTT performance may vary between the three static conditions. One-way repeated-measures ANOVAs were used to determine whether \bar{r} , σ_r , and \hat{r} were significantly different between the start-up, embedded, and final static conditions.

4.4 Results

4.4.1 Exploratory data analysis

4.4.1.1 Three-dimensional surface plot

Three-dimensional surface plots clearly demonstrate how average mean, standard deviation, and maximum resultant distances (\bar{r} , σ_r , and \hat{r}) vary across frequency and acceleration, as shown in Figure 4.3. to Figure 4.5, respectively. In general, magnitudes of the average \bar{r} , σ_r , and \hat{r} increased with increases in acceleration. They also show nonlinear relationships with frequency: they increase when frequency increases from 0.125 Hz, peak at 0.5 Hz, and drop rapidly when frequency increases from 0.5 Hz to 1 Hz. Although magnitudes between the average \bar{r} , σ_r , and \hat{r} are different, their patterns across frequency and acceleration are similar.

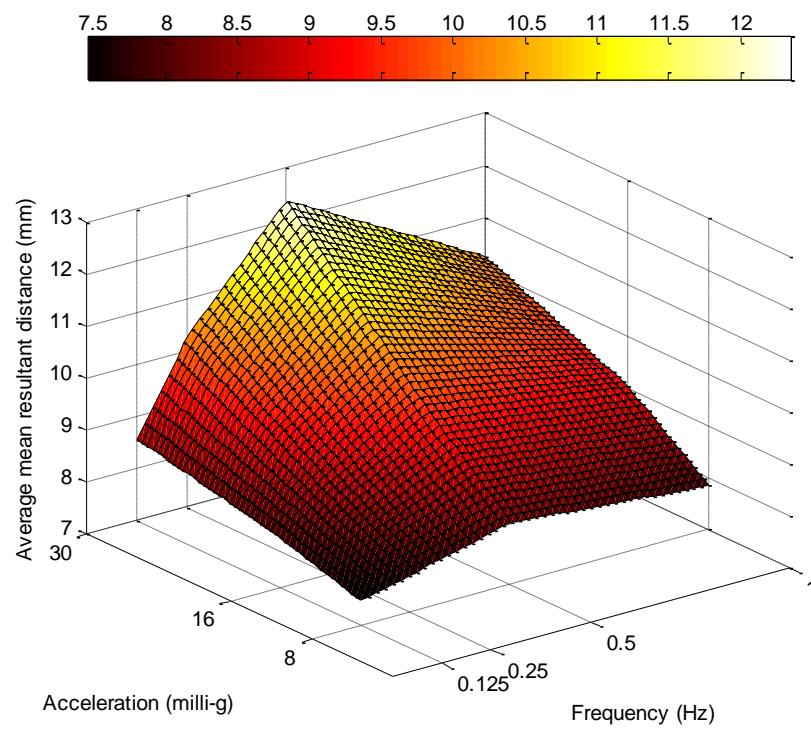


Figure 4.3. Three-dimensional surface plot of average mean resultant distance.

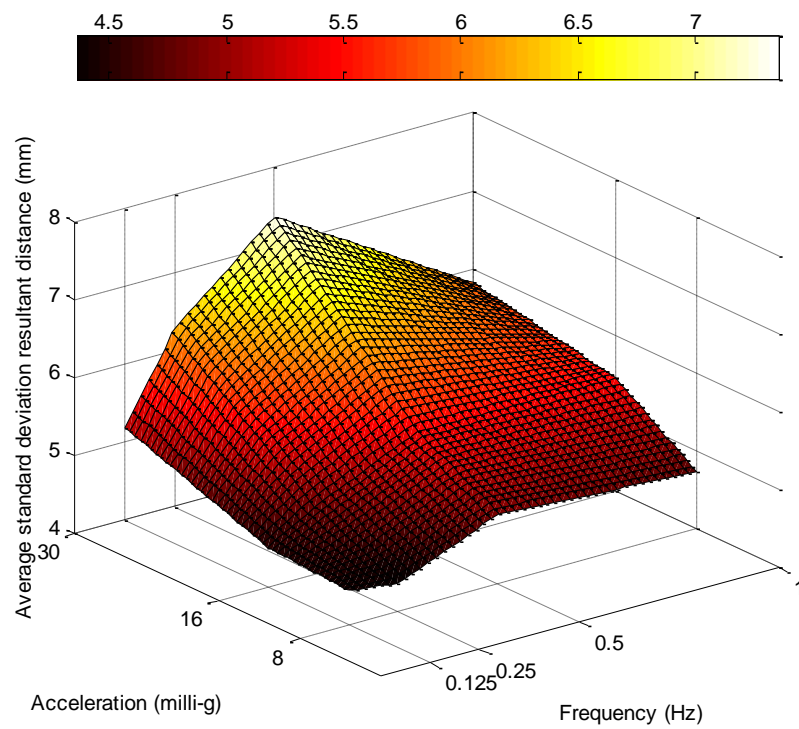


Figure 4.4. Three-dimensional surface plot of average standard deviation resultant distance.

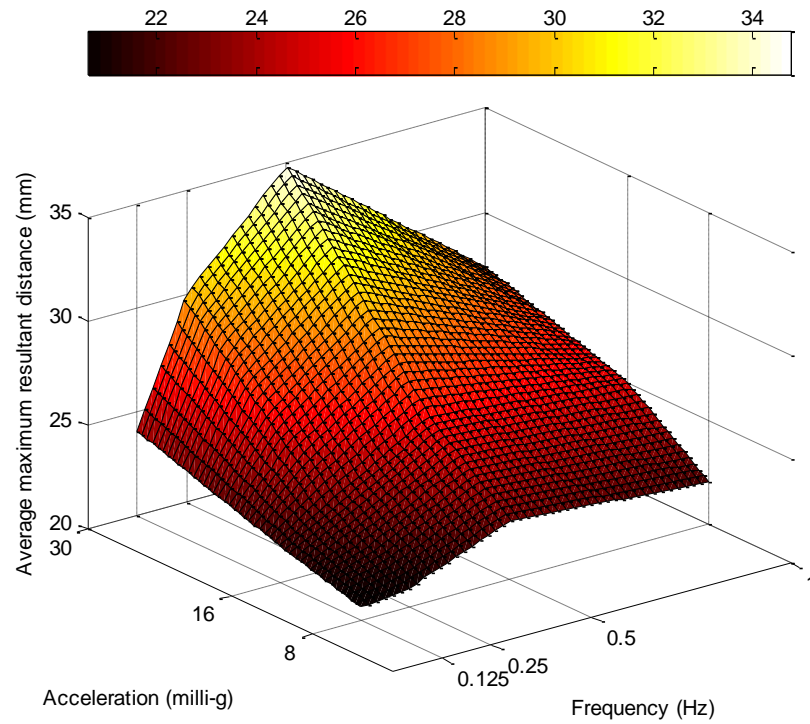


Figure 4.5. Three-dimensional surface plot of average maximum resultant distance.

4.4.1.2 Box plots

Figure 4.6. to Figure 4.8 show box plots of the mean, standard deviation, and maximum resultant distances (\bar{r} , σ_r , and \hat{r}) determined for all participants, both fore-aft and lateral motion groups. The box plots of the \bar{r} , σ_r , and \hat{r} share a number of common features. First, magnitudes of \bar{r} , σ_r , and \hat{r} are the smallest under static conditions when compared with other motion conditions. At least 75% of the \bar{r} and σ_r , are smaller than 10 mm, as shown in Figure 4.6. and Figure 4.7 respectively. The magnitudes of \hat{r} are generally higher than \bar{r} and σ_r . The 75th percentiles of \hat{r} are between 20 to 25 mm. The magnitudes of these factors, measured under static conditions, form references for comparing with motion conditions.

Second, the dispersions of \bar{r} , σ_r , and \hat{r} measured under motion conditions are greater than static conditions; this is as expected. The dispersions also increase with increases in acceleration. Third, distributions of \bar{r} , σ_r , and \hat{r} are different between accelerations. At 8 and 16 milli-g, \bar{r} , σ_r , and \hat{r} are distributed nearly symmetrically about the median, whereas distributions of \bar{r} , σ_r , and \hat{r} under 30 milli-g are positively skewed (right-skewed). Furthermore, most outliers appear on the large magnitude side, except one outlier: \hat{r} measured under 0.25 Hz 8 milli-g condition appears on the small magnitude side.

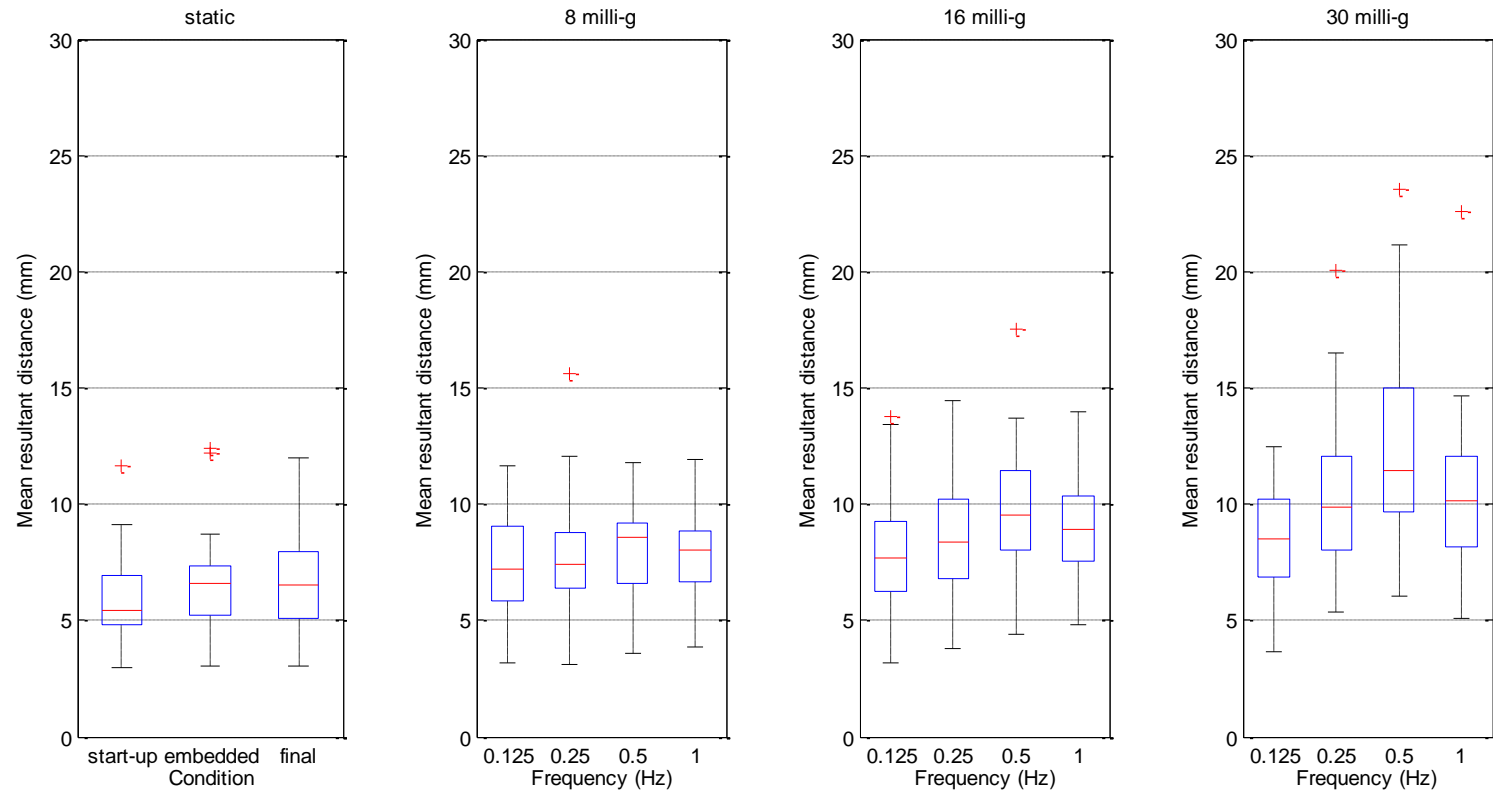


Figure 4.6. Box plots of mean resultant distance measured under fore-aft and lateral motion conditions. On each box, the central mark is the median, lower and upper edges of the box are respectively the 25th and 75th percentiles, whiskers extend to the maximum and minimum data points not considered as outliers, and outliers (+), are plotted individually.

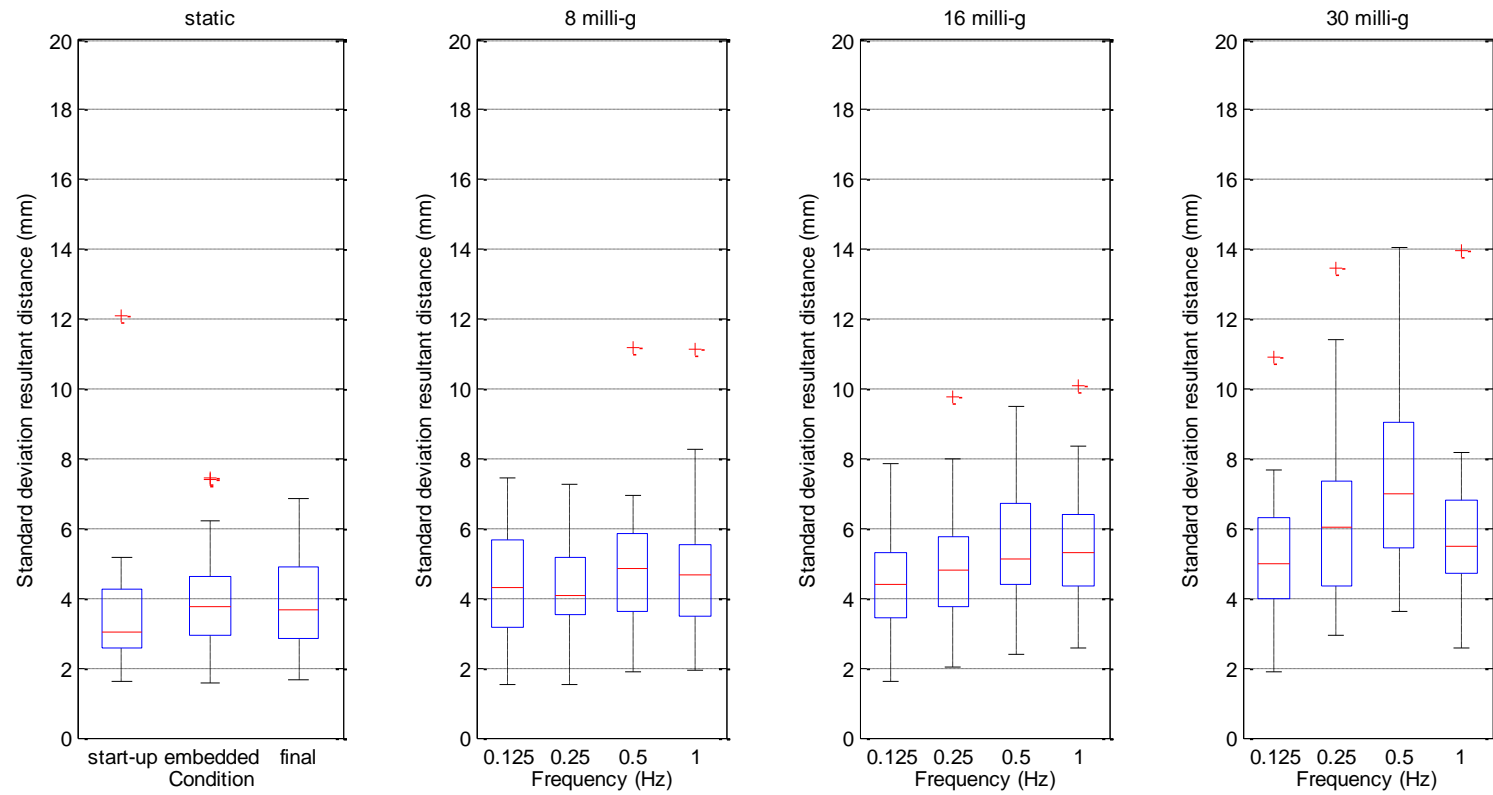


Figure 4.7. Box plots of standard deviation resultant distance measured under fore-aft and lateral motion conditions, as in Figure 4.6.

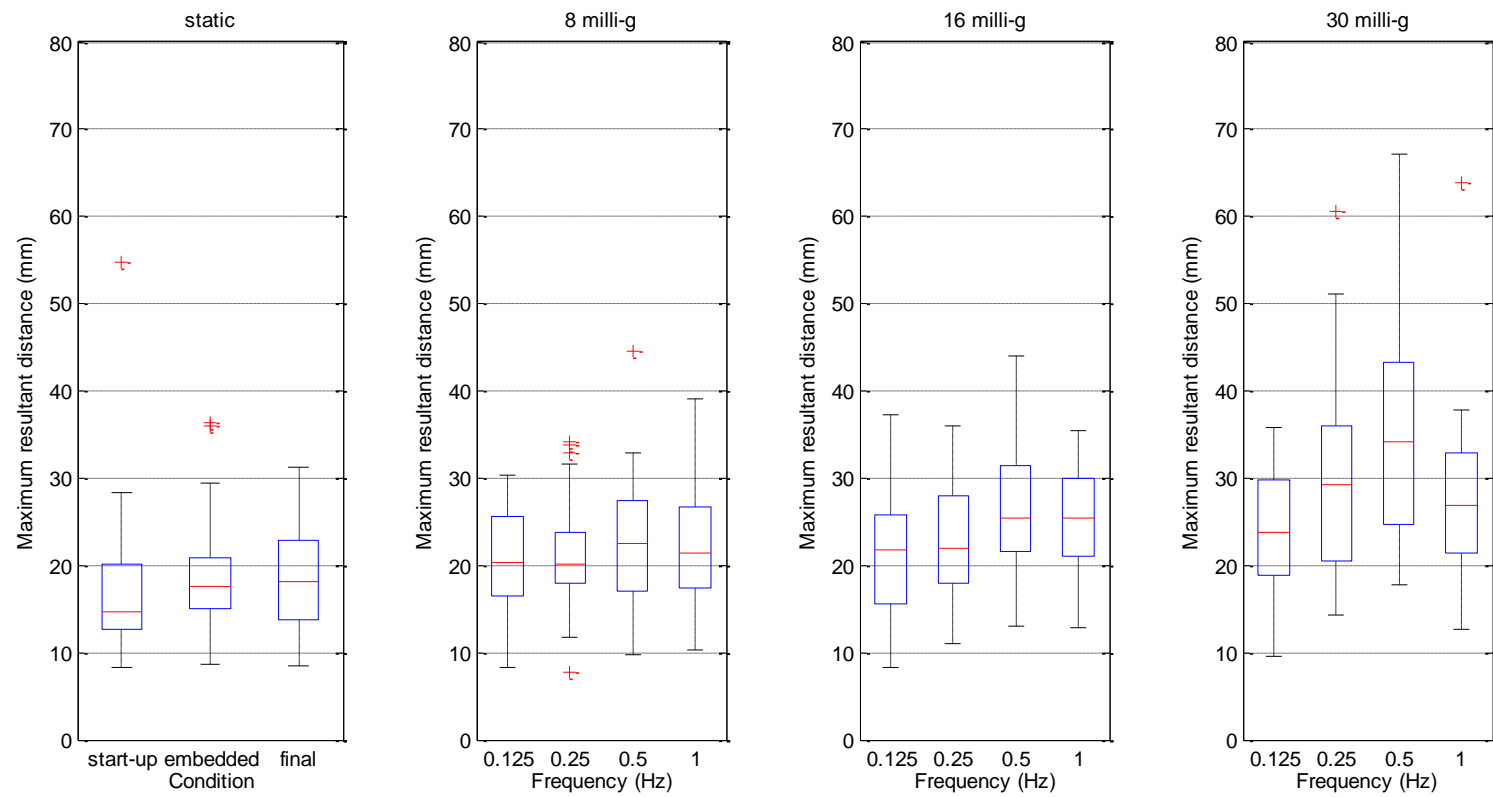


Figure 4.8. Box plots of maximum resultant distance measured under fore-aft and lateral motion conditions, as in Figure 4.6.

4.4.2 Statistical analysis on mean resultant distance

4.4.2.1 Effects of 8 milli-g motion

The lowest measured acceleration, 8 milli-g, causes significant increases in \bar{r} ($M = 7.81$, $SD = 2.11$) compared with the embedded static condition ($M = 6.51$, $SD = 1.91$), $t(159) = 10.9$, $p\text{-value} < 0.001$. This increase equates to a moderate to large effect size of 0.65 (Cohen's d).

4.4.2.2 Effects of frequency and acceleration

A two-way repeated-measures ANOVA shows that both frequency, $F(3, 117) = 34.1$, $p\text{-value} < 0.001$, and acceleration, $F(2, 78) = 103.4$, $p\text{-value} < 0.001$, significantly affect \bar{r} , as shown in Figure 4.9. The error bars in this and the following figures, if any, represent the standard error (S.E.) of the data. \bar{r} significantly increases with increases in acceleration. The largest increase occurs at 30 milli-g. Compared with the embedded static condition, 30 milli-g motion produces an average increase in \bar{r} , representing a degradation in average CTT accuracy, that equates to a large effect size of 1.66 (Cohen's d).

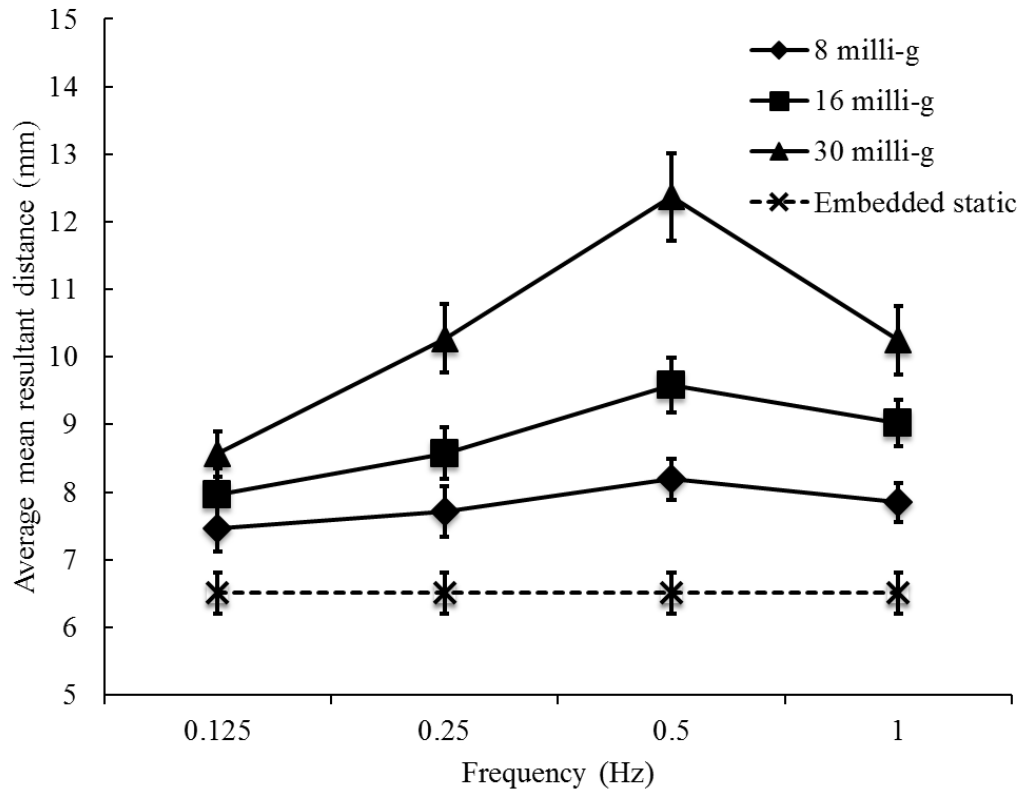


Figure 4.9. Average mean resultant distance (mean \pm S.E.) of all participants ($N = 40$) across frequency and acceleration compared with the embedded static condition.

\bar{r} has a nonlinear relationship with frequency, where \bar{r} increases with increases in frequency from 0.125 Hz to 0.5 Hz. After peaking at 0.5 Hz, \bar{r} decreases when frequency increases from 0.5 to 1 Hz. Comparing the reduction in average CTT performance caused by the peak reduction occurring at 0.5 Hz with the least reduction at 0.125 Hz, this equates to a large effect size of 0.87 (Cohen's d).

Frequency and acceleration showed a significant interaction, $F(6, 234) = 8.9$, $p\text{-value} < 0.001$, where the condition that provoked the largest increase in \bar{r} , 30 milli-g at 0.5 Hz, shows a greater reduction in average CTT performance in combination than either main effect alone. 30 milli-g motion at 0.5 Hz produces a reduction in average CTT performance with a large effect size of 1.84.

4.4.2.3 Effects of gender

A mixed-design three-way ANOVA with frequency and acceleration as within-subjects factors and gender as between-subjects factor shows that there was no significant effect of gender on average CTT performance $F(1, 38) = 0.059$, $p\text{-value} = 0.809$.

4.4.2.4 Effects of motion direction

A mixed-design three-way ANOVA with frequency and acceleration as within-subjects factors and motion direction as between-subjects factor shows that there was no significant effect of motion direction on CTT performance, $F(1, 38) = 0.41$, $p\text{-value} = 0.526$.

4.4.2.5 Difference between static conditions

A one-way repeated-measures ANOVA shows that the mean resultant distance (\bar{r}) significantly differs between the three static conditions, $F(2, 78) = 6.64$, $p\text{-value} = 0.002$. \bar{r} significantly increases from the start-up static condition ($M = 5.86$, $SD = 1.68$) to the embedded static condition ($M = 6.51$, $SD = 1.93$), $t(39) = -2.50$, $p\text{-value} = 0.017$, but the embedded static condition does not significantly differ from the final static condition ($M = 6.65$, $SD = 2.04$), $t(39) = -0.69$, $p\text{-value} = 0.50$. Difference between the start-up against final static conditions equates to a small to moderate effect size of 0.42 (Cohen's d). The effect size is smaller than those for frequency (Cohen's $d = 0.87$) and acceleration (Cohen's $d = 1.66$).

4.4.3 Statistical analysis on standard deviation resultant distance

4.4.3.1 Effects of 8 milli-g motion

The lowest measured acceleration, 8 milli-g, causes a significant increase in σ_r ($M = 4.61$, $SD = 1.57$) compared with the embedded static condition ($M = 3.87$, $SD = 1.31$), $t(159) = 7.18$, $p\text{-value} < 0.001$, which equates to an effect size of 0.51 (Cohen's d). Compared with the embedded static conditions, the 8 milli-g motion significantly increased variance in CTT.

4.4.3.2 Effects of frequency and acceleration

A two-way repeated-measures ANOVA shows that both frequency, $F(3, 117) = 19.0$, $p\text{-value} < 0.001$, and acceleration, $F(2, 78) = 51.4$, $p\text{-value} < 0.001$, significantly affect σ_r . The σ_r , variance in CTT, significantly increases with increases in acceleration, as shown in Figure 4.10. . The largest increase in σ_r occurs at 30 milli-g. Difference of the σ_r between the embedded static condition and 30 milli-g motion equates to a large effect size of 1.48 (Cohen's d).

σ_r , variance in CTT, has a nonlinear relationship with frequency. σ_r increases with increases in frequency from 0.125 Hz to 0.5 Hz, and σ_r decrease from 0.5 to 1 Hz. A frequency of 0.5 Hz causes a peak performance degradation. Compared with 0.125 Hz conditions, which caused the least performance degradation among the tested frequencies, 0.5 Hz causes a fluctuating CTT performance degradation equating to a large effect size of 0.79 (Cohen's d).

Frequency and acceleration show a significant interaction, $F(6, 234) = 5.164$, $p\text{-value} < 0.001$. The largest increase in σ_r , variance in CTT, is provoked by 30 milli-g at 0.5 Hz motion. The acceleration and frequency in combination show a greater increase in σ_r than either main effect alone. 30 milli-g motion at 0.5 Hz produces a degradation in fluctuating CTT performance with a large effect size of 1.61

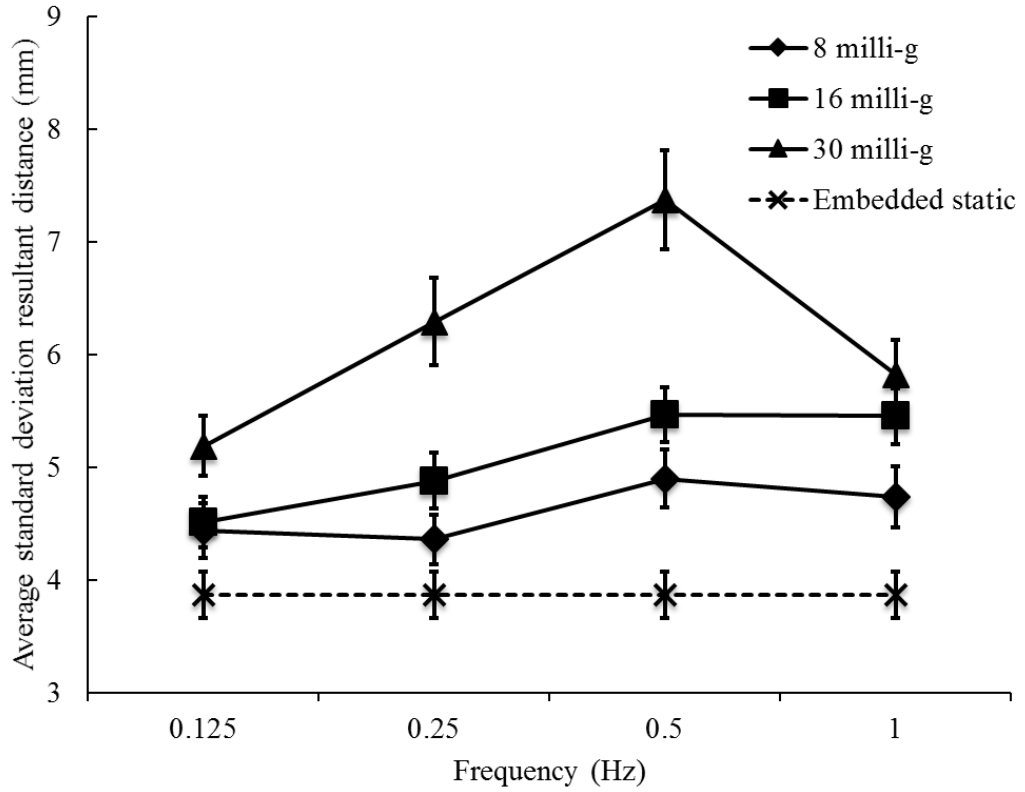


Figure 4.10. Average standard deviation resultant distance (mean \pm S.E.) of all participants ($N = 40$) across frequency and acceleration compared with the embedded static condition.

4.4.3.3 Effects of gender

A mixed-design three-way ANOVA with frequency and acceleration as within-subjects factors and gender as between-subjects factor shows that the effect of gender is not significant on σ_r , $F(1, 38) = 0.045$, $p\text{-value} = 0.833$.

4.4.3.4 Effects of motion direction

A mixed-design three-way ANOVA with frequency and acceleration as within-subjects factors and motion direction as between-subjects factor shows that σ_r is not significantly affected by motion direction, $F(1, 38) = 0.008$, $p\text{-value} = 0.928$.

4.4.3.5 Difference between static conditions

Differences of standard deviation resultant distance (σ_r), fluctuating CTT performance, between the three static conditions, $F(2, 78) = 2.17$, $p\text{-value} = 0.121$, are not significant.

4.4.4 Statistical analysis on maximum resultant distance

4.4.4.1 Effects of 8 milli-g motion

Compared with the embedded static condition ($M = 18.6$, $SD = 6.14$), the lowest measured acceleration, 8 milli-g, significantly increases \hat{r} , maximum excursion of CTT performance, ($M = 21.6$, $SD = 6.43$), $t(159) = 7.49$, $p\text{-value} < 0.001$. This increase equates to a moderate effect size of 0.48 (Cohen's d).

4.4.4.2 Effects of frequency and acceleration

A two-way repeated-measures ANOVA shows that both frequency, $F(3, 117) = 24.7$, $p\text{-value} < 0.001$, and acceleration, $F(2, 78) = 67.1$, $p\text{-value} < 0.001$, significantly affect \hat{r} , as shown in Figure 4.11. The \hat{r} significantly increases with increases in acceleration. The largest increase occurs at 30 milli-g. A degradation in maximum excursion of CTT performance that equates to a large effect size of 1.48 (Cohen's d) is produced when comparing 30 milli-g motion with the embedded static condition.

\hat{r} has a nonlinear relationship with frequency, where \hat{r} increases with increases in frequency from 0.125 Hz to 0.5 Hz, and \hat{r} decrease when frequency increases from 0.5 to 1 Hz. The performance degradation caused by the peak performance degradation that occurs at 0.5 Hz, compared with 0.125 Hz condition, equates to a large effect size of 0.85 (Cohen's d).

Interaction between frequency and acceleration is significant, $F(6, 234) = 7.034$, $p\text{-value} < 0.001$. 30 milli-g at 0.5 Hz provoked the largest increase in \hat{r} . The frequency and acceleration combination shows an increase in \hat{r} greater than either main effect alone. Compared with the embedded static condition, 30 milli-g motion at 0.5 Hz produces an increase in \hat{r} equating a large effect size of 1.63.

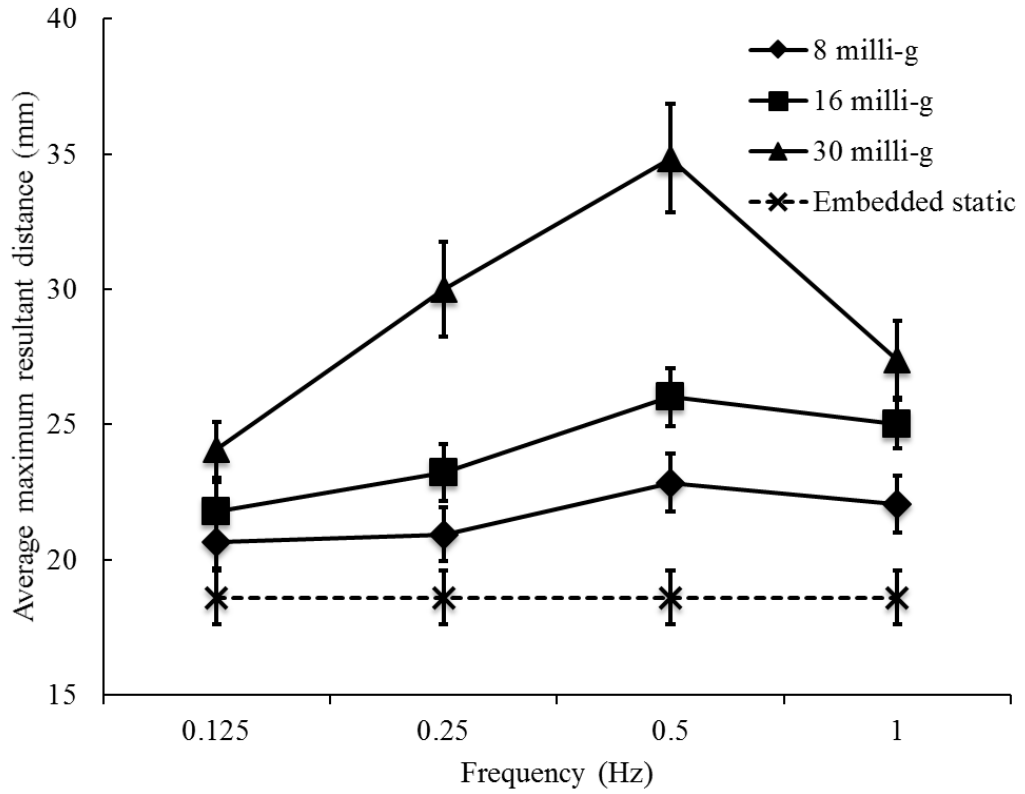


Figure 4.11. Average maximum resultant distance (mean \pm S.E.) of all participants ($N = 40$) across frequency and acceleration compared with the embedded static condition.

4.4.4.3 Effects of gender

A mixed-design three-way analysis of variance ANOVA with frequency and acceleration as within-subjects factors and gender as between-subjects factor shows that gender effect on \hat{r} is not significant, $F(1, 38) = 0.022$, $p\text{-value} = 0.884$.

4.4.4.4 Effects of motion direction

A mixed-design three-way ANOVA with frequency and acceleration as within-subjects factors and motion direction as between-subjects factor shows that effect of motion direction on \hat{r} is not significant, $F(1, 38) = 0.000$, $p\text{-value} = 0.999$.

4.4.4.5 Difference between static conditions

A one-way repeated-measures ANOVA shows that maximum resultant distance (\hat{r}), maximum excursion of the CTT performance between the three static conditions, $F(2, 78) = 2.31$, $p\text{-value} = 0.107$, are not significantly different.

4.5 Discussion

The current study used a continuous tracking task (CTT) to investigate effects of low-frequency, low-acceleration motion on manual task performance. The CTT required participants to hold a laser pointer and aim a laser light dot as close as possible to the centre of a target. Task performance was quantified using mean (\bar{r}), standard deviation (σ_r), and maximum (\hat{r}) resultant distances between the laser light dot and the centre of the target. These mean (\bar{r}), standard deviation (σ_r), and maximum (\hat{r}) resultant distances respectively represent average accuracy, fluctuation, and maximum excursion of CTT performance. Results of this chapter show that increases in \bar{r} , σ_r , and \hat{r} occurred even at the lowest tested acceleration (8 milli-g). When compared with the embedded static condition, 8 milli-g motion increases \bar{r} , σ_r , and \hat{r} with moderate effect sizes ranging from 0.48 to 0.65. This indicates that task performance measured at 8 milli-g can be 0.48 to 0.65 standard deviations below performance in embedded static conditions. It should be noted that ISO 10137:2007 defines motion at a magnitude of 8 milli-g as satisfactory for office buildings with frequencies ranging between 0.1 Hz and 0.5 Hz, suggesting that the effects of the motion on people are likely to be negligible.- This finding is in contrast to that of Burton et al. (2011), who concluded that task performance is unlikely to be affected within the range of accelerations that might realistically occur in wind-excited buildings, i.e. accelerations up to about 30 milli-g. Potential causes of the differing results between studies will be discussed in detail in a later part of this discussion.

4.5.1 Effects of motion on average accuracy, fluctuation, and maximum excursion of CTT performance

Effects of motion on the trends of average accuracy, fluctuation, and maximum excursion of CTT performance in response to motion are similar. This is supported by a number of observations. Three-dimensional surface plots, Figure 4.3 to Figure 4.5, show that the patterns of mean, standard deviation, and maximum resultant distances (\bar{r} , σ_r , and \hat{r}) vary similarly across frequency and acceleration. Box plots, Figure 4.6 to Figure 4.8, show that magnitudes and dispersions of \bar{r} , σ_r , and \hat{r} increase with increases in acceleration. The magnitudes and dispersions also consistently increase from 0.125 Hz to 0.5 Hz, then drop rapidly when frequency increases from 0.5 Hz to 1 Hz. The distributions of \bar{r} , σ_r , and \hat{r} are positively skewed at 30 milli-g while at 8 and 16 milli-g the distributions are nearly symmetrical about the median. A majority of outliers consistently appear with large magnitudes of \bar{r} , σ_r , and \hat{r} .

Statistical analyses show that the effects of frequency, acceleration, and their interaction cause significant differences on \bar{r} , σ_r , and \hat{r} between motion conditions. Effect sizes between \bar{r} , σ_r , and \hat{r} are comparable, as shown in Figure 4.12. Since the effects of motion on the trends of average accuracy, fluctuation, and maximum excursion of CTT performance in response to motion are similar, either average accuracy, fluctuation, or maximum excursion of CTT performance (\bar{r} , σ_r , and \hat{r}) can be used to demonstrate effects of motion on task performance. Later parts of this discussion will use CTT performance as a collective reference to average accuracy (\bar{r}), fluctuation (σ_r), and maximum excursion (\hat{r}) of CTT performance.

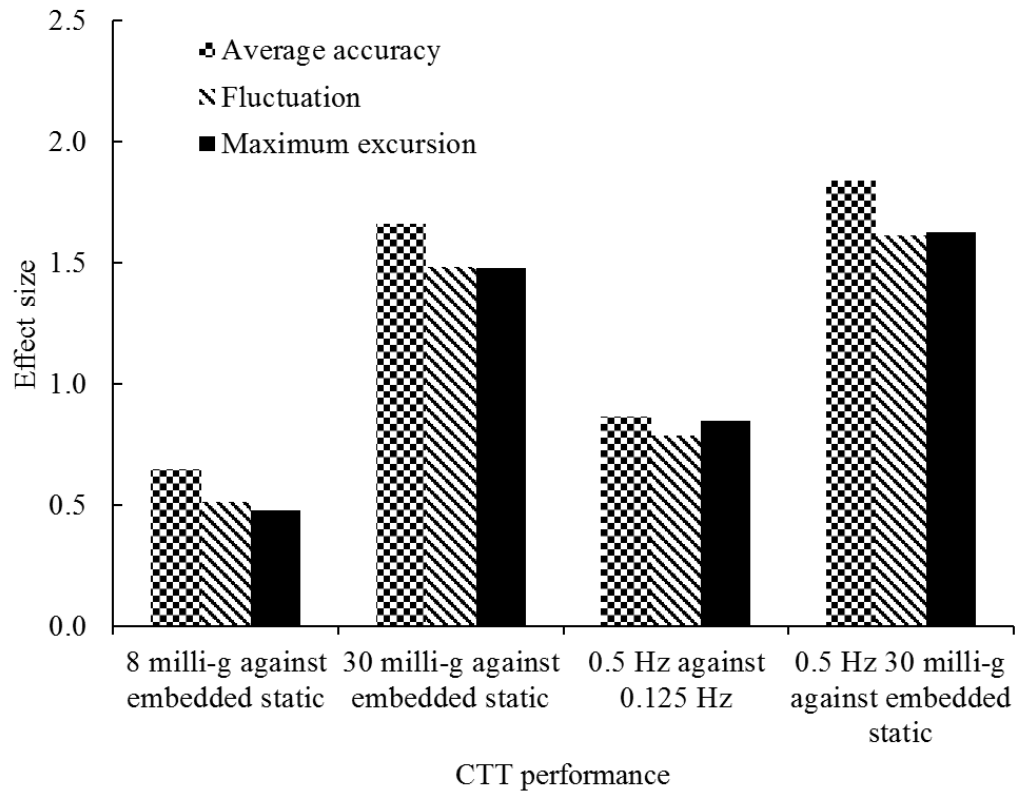


Figure 4.12. Effect sizes of average, fluctuation, and maximum excursion of CTT performance.

4.5.2 Effects of acceleration and frequency on CTT performance

Acceleration has a strong, near-linear, inverse relationship with CTT performance; average accuracy, fluctuation, and maximum excursion of the CTT performance decrease with increases in acceleration. Compared with the embedded static condition, the maximum acceleration of 30 milli-g caused a large degradation with effect sizes of 1.66 for average accuracy, 1.48 for both fluctuation and maximum excursion of the CTT performance. This means that CTT performance during 30 milli-g can be 1.7 to 1.5 standard deviations below performance in embedded static conditions.

Frequency has a complex nonlinear relationship with task performance including average accuracy, fluctuation, and maximum excursion of the CTT performance. It was found that the performance degradation peaks at 0.5 Hz, though the actual peak is likely to occur in the region around 0.5 Hz, as only four discrete frequencies were tested. The effects of frequency are large (Cohen, 1988). Compared with 0.125 Hz, 0.5 Hz motion reduces average accuracy and increases variance and maximum excursion of the CTT performance with effect sizes of 0.87, 0.79, and 0.85 respectively. These effect sizes equate to degradations of approximately 0.8 standard deviation. Furthermore, frequency and acceleration interact, producing a greater performance degradation than the main effects of acceleration or frequency alone. Participants performed the worst during an acceleration of 30 milli-g at 0.5 Hz.

Motion-induced performance degradations are consistent with the observations reported by Goto et al. (1990) and Irwin and Goto (1984), though this chapter examined task performance over a larger acceleration and frequency range than either studies. However, the results of this chapter differ greatly from Burton et al. (2011) who tested manual task performance using bi-directional, narrow-band random motion over a similarly large range of accelerations and frequencies. It had been expected that bi-directional, narrow-band random motion would more readily induce nausea and disrupt task performance (Burton et al., 2005). Burton et al. (2011) however found no significant performance degradation and concluded that task performance is unlikely to be affected within the range of accelerations that might realistically occur due to wind-induced building motion, i.e. accelerations up at about 30 milli-g. This chapter shows that moderate degradations in task performance can occur at as low as 8 milli-g, reducing performance by 0.48 to 0.65 standard deviation relative to a static condition.

There are two possible reasons for the differing results. First, almost all participants in Burton et al. (2011) were self-reported ‘gamers’ (people who play video games) and were likely skilled at the task. Using the self-reported ‘gamers’ as participants may have produced ‘ceiling effects’ (high scores on the dependent measures with low variation). As a measure of task performance, Burton et al. (2011) used a laser-gun controlled video game requiring participants to shoot at discrete targets, measured as hits or misses, not a continuous or absolute measure of accuracy. The task may have been insensitive to measuring actual performance degradations. Furthermore, McLeod and Griffin (1988) showed that effects of vertical translational motion on a continuous tracking task were more prominent than on a discrete tracking task. This suggests that using the video game, a kind of discrete tracking task, may be a major factor that contributed to the neutral findings reported by Burton et al. (2011). This seems reasonable given that about half the participants in Burton et al. (2011) reported difficulty balancing.

Second, using bi-directional, narrow-band random motion may be another factor leading to the neutral findings reported by Burton et al. (2011). It has known that motion-induced body sway can degrade manual task performance (Wertheim, 1998). The motion-induced body sway is likely to be proportional to the inertial force acting on a human body, which in turn, is proportional to acceleration magnitude. Burton et al. (2011) used 720-second narrow-band random motion as a motion stimulus. During the 720-second narrow-band random motion the occurrence probability of relatively high acceleration motion cycles was relatively low. This suggests that a simultaneous occurrence of the relatively high acceleration motion cycles and appearance of a target in the video game was likely to be infrequent. Hence, participants may have performed the video game task at relatively low acceleration for a majority of time, resulting in the neutral findings.

4.5.3 Potential causes of motion-induced performance degradations

4.5.3.1 Increase in inertial force

Results of this chapter show that increases in acceleration significantly decrease CTT performance. As inertial force is directly proportional to acceleration, increases in acceleration, at least within the acceleration range tested, monotonically exert greater inertial force on the trunk and limbs of a human body. This increase in inertial force may lead to several means by which task performance is degraded.

For example, inertial force-induced body motion can degrade task performance due to visual impairment. This has been discussed in studies investigating manual task performance in transportation environments (for example Allen et al., 1973; McLeod and Griffin, 1988, 1989). Visual impairment can be due to motion-induced flexing of the spine and nodding of the head (Allen et al., 1973). These body movements can provoke relative movement between the head and shoulder and the target, resulting in visual blurring that in turn degrades CTT performance. Further, increases in acceleration can enhance inertial forces acting on the human body thus intensifying the visual blurring. McLeod and Griffin (1988) suggest that impaired visual ability due to relative translational movement between participants' eyes and the display may be responsible for degradation of tracking task performance at 4.0 and 5.0 Hz vertical motion conditions with an RMS acceleration magnitude of approximately 200 milli-g.

It should be noted that the frequency and acceleration of the transportation motion conditions tested in previous studies are significantly higher than those tested in the current study. Hence, the effects of visual impairment on task performance in transportation are likely to be more prominent than those in wind-induced building motion environment. However, the human body is more flexible in the horizontal direction than the vertical direction, resulting in larger flexing of the spine, nodding of the head and/or relative movement between participants' eyes and the display. This may have enhanced the effects of visual blurring. Therefore, the possibility of task performance degradation in wind-induced building motion environments due to visual impairment should not be ruled out.

An increase in inertial force may also disrupt balance. Participants may find it difficult to maintain balance while performing a manual task under motion conditions with a peak acceleration of up to 30 milli-g (Burton et al., 2011). While maintaining balance is mostly an automatic process, studies have shown that challenges to balance requires some conscious attention, which causes a degradation in cognitive performance (Andersson et al., 2002; Chong et al., 2010; May et al., 2009; Mersmann et al., 2013). Therefore, higher accelerations may require conscious attention to maintain balance, which decreases the attention available to undertake the CTT, thus degrading performance.

Vibration breakthrough can be another source causing CTT performance degradation. Vibration breakthrough is a mechanism that associates transmission of motion-induced activity at the hand, via a control of manual tasks, through system dynamics to produce activity of a controlled element, such as a cross-hair on a display, at the motion frequencies (Allen et al., 1973; McLeod and Griffin, 1989). In the current study, an increase in acceleration can increase the inertial force acting on the limb holding the laser pointer and hence increase the movement of the laser light dot on the target. Although participants may attempt to actively adjust the limb and laser pointer to compensate for the increase in laser light dot movement, they are unlikely to be able to accurately estimate the increased inertial force and/or the increased limb and laser pointer movements. This may in turn induce extraneous control action that degrades task performance (Allen et al., 1973). Furthermore, this active adjustment on the limb and laser pointer consumes additional attention resources originally assigned to undertake the CTT (McLeod and Griffin, 1989).

Motion has been recognised as a primary stimulation that causes motion sickness and/or sopite syndrome. Increases in acceleration enhances stimulation intensity. Prolonged exposure to provocative stimulations, such as vehicular or wind-induced building motion, can induce symptoms such as nausea, vomiting, disinclination to work, distraction from work activities, tiredness, and low motivation and mood (for example Goto, 1983; Hansen et al., 1973; Lamb et al., 2014; Walton et al., 2011). These symptoms can cause discomfort and inability to work (Graybiel and Knepton, 1976; Lackner, 2014; Reason and Brand, 1975). In addition, motion sickness can be an adverse psychological effect. Studies have shown that the development of motion sickness symptoms can induce anxiety in some individuals (Jacob et al., 1993; Jacob et al, 1995). This anxiety can, in turn, increase the difficulty to respond to experimental tasks (Pacheco-Unguetti et al., 2010). The effects of sopite syndrome on CTT performance are discussed in the next chapter.

4.5.3.2 Frequency response characteristics of an upright human body

Results of this chapter show that task performance decreases in an inverted U-pattern, peaking at 0.5 Hz. The frequency response characteristics of the human body are a potential cause for the patterns of CTT performance reduction across frequencies from 0.125 Hz to 1 Hz. The patterns of performance reduction across frequency are similar to Burton et al. (2006), who measured accelerations at the back of seated participants exposed to sinusoidal motion at a peak acceleration of 13.5 milli-g, as shown in Figure 4.13. Burton et al. (2006) found that the acceleration increases from 0.15 Hz, peaks at 0.5 Hz, then decreases from 0.5 Hz to 1 Hz.

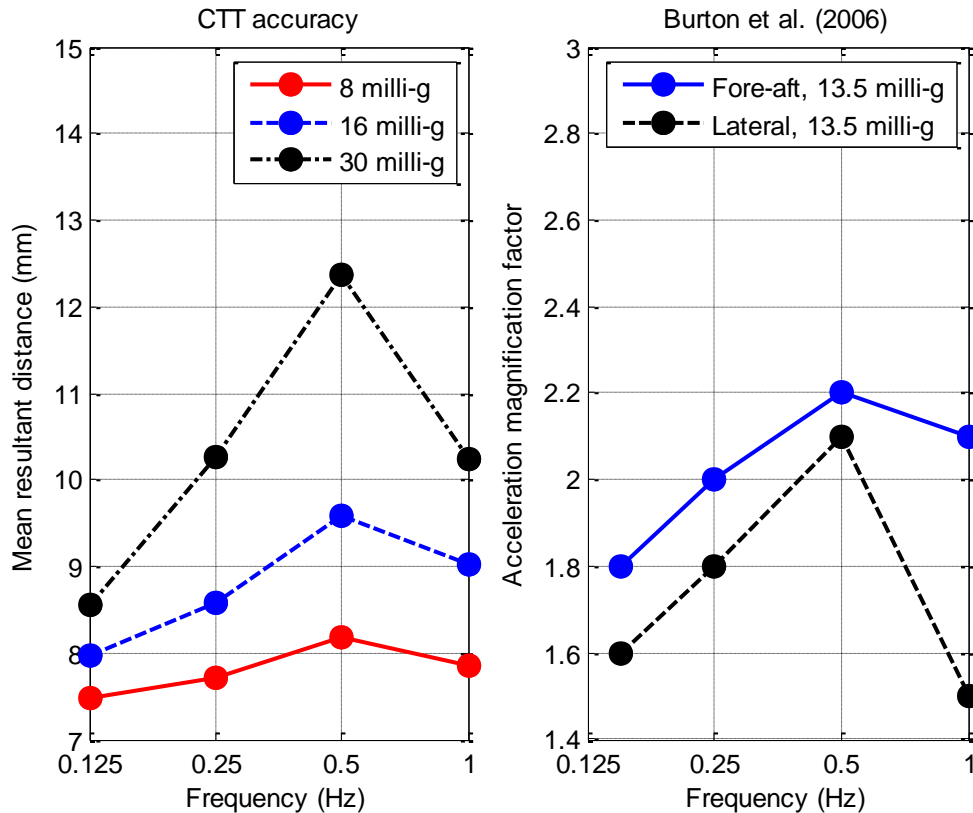


Figure 4.13. A comparison between the patterns of average accuracy of CTT performance and the acceleration magnification factor measured at the back by Burton et al. (2006).

Resonance of a human body may be responsible for the largest performance degradation due to frequency effects. Shin et al. (2006) found the resonant frequencies of standing humans exposed to fore-aft motion are between 0.60 to 0.68 Hz. This range is slightly higher than the peak performance degradation found at 0.5 Hz in this chapter. The true peak performance degradation may occur in the 0.60 to 0.68 Hz range.

However, differences in the postures used by the participants in the two studies may have altered the resonant frequency. Shin et al. (2006) restricted participants' knee, hip, and neck to a fixing assembly, as shown in Figure 4.14. This would have increased the stiffness of the body. With the restriction, a standing human body can be modelled as a single-degree-of-freedom inverted pendulum. Since the resonant frequency of a single-degree-of-freedom inverted pendulum is proportional to the square root of stiffness, increased body stiffness may have resulted in a higher resonant frequency of a standing human body.

Alternatively, the posture used in the current study may have reduced the resonant frequency of a human body. Participants stood with one arm approximately perpendicular to their trunk to hold the laser pointer. This posture redistributed body mass to the upper part of the body, increasing the moment of inertia about the ankle joint, consequently reducing the resonant frequency. By considering results of this chapter and Shin et al. (2006), it is estimated that the resonant frequency of a free standing human is likely to be between 0.5 and 0.68 Hz. In particular, CTT performance appears to be most affected by frequency in the range of a human's resonant frequency.

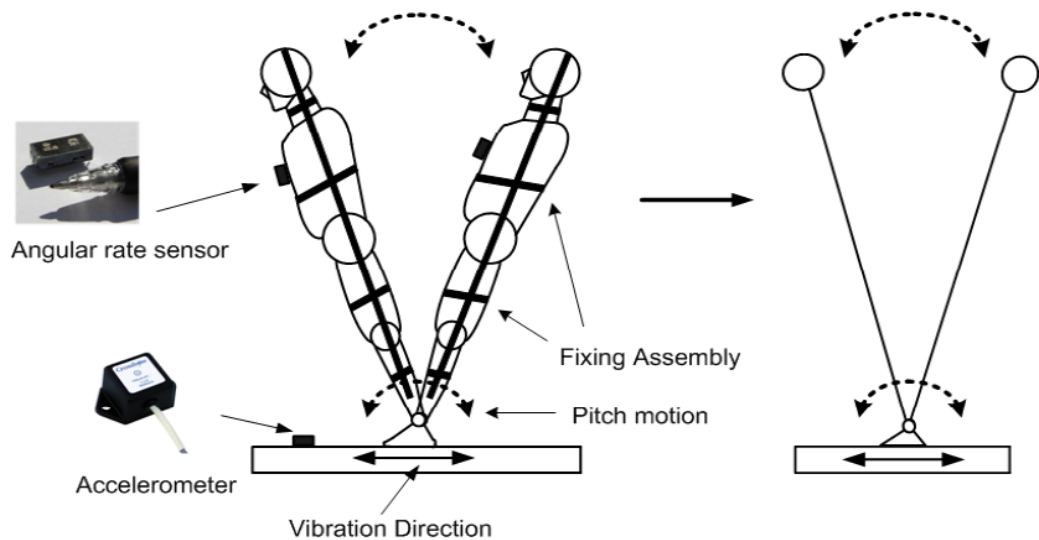


Figure 4.14. An experimental setup used to investigate the resonant frequency of human body (reproduced from Figure 1 of Shin et al., 2006).

4.5.4 Relative contribution on degradation of CTT performance between acceleration and frequency

Evidently, acceleration contributed more than frequency to the degradation of CTT performance within the ranges that are relevant to wind-induced building motion. The results of this chapter show that effect sizes of acceleration are larger than frequency, as shown in Figure 4.15. The effect sizes of acceleration can be twice that of frequency.

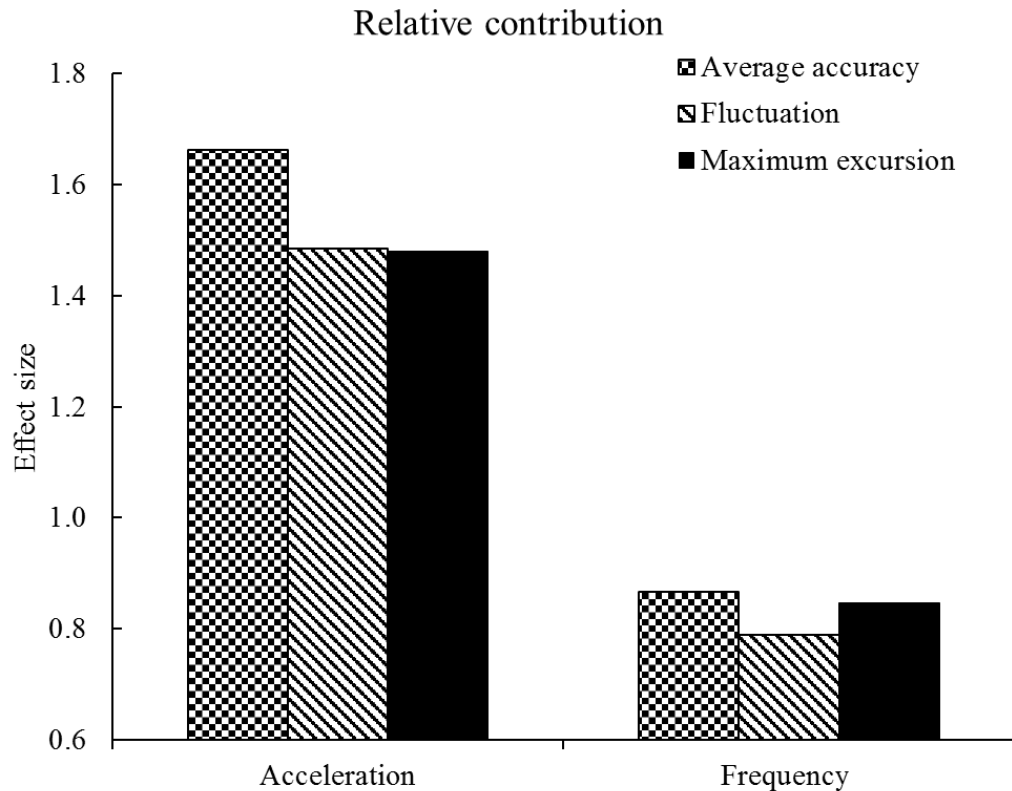


Figure 4.15. Relative contributions to CTT performance degradation by acceleration and frequency.

Since inertial force is directly proportional to acceleration, an increase in acceleration can further degrade task performance. Acceleration effects can be unbounded and theoretically be increased until participants fail to perform the manual task due to, for example, a loss of balance.

In contrast, frequency effects are likely to be limited. Within the frequency range of 0.125 Hz and 1 Hz, local maxima of \bar{r} , σ_r , and \hat{r} appear at 0.5 Hz, which is close to the resonant frequency of the human body (e.g. such as with restricted movements of the hips and knees according to Shin et al. 2006). An amplification of body sway and a corresponding degradation in task performance are likely to be bounded by the local maxima. The pattern of the frequency response characteristic of the human body is similar to frequency response curves of under-damped systems in which local maxima appear near the resonant frequency, as shown in Figure 4.16.

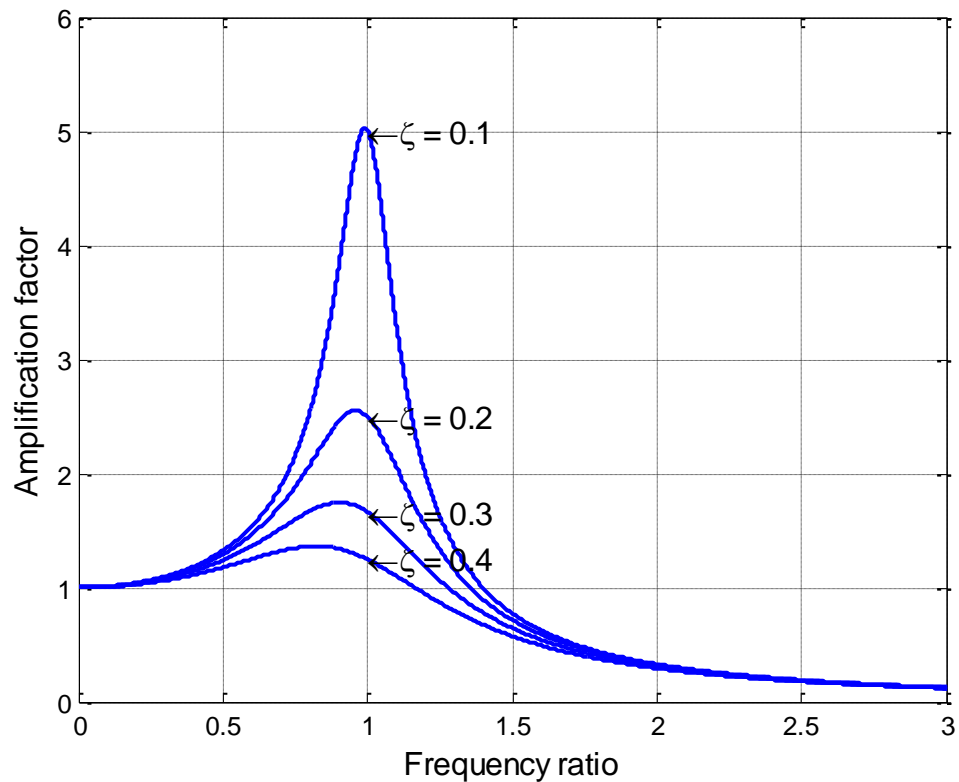


Figure 4.16. Frequency response curve of under damped mechanical systems. Damping ratios vary from 0.1 to 0.4 of critical.

4.5.5 Implications on criteria and recommendations for occupant response to wind-induced building motion

The current criteria and recommendations were established based on perception thresholds and/or complaint rate/tolerance of wind-induced building motion for buildings used by the general population (International Organization for Standardization, 1984, 2007). No criteria or recommendations consider the effects of wind-induced building motion on manual task performance. Figure 4.17 shows a comparison between degradations of manual task performance with the peak acceleration criteria suggested by ISO 10137:2007 (International Organization for Standardization, 2007). The peak acceleration criteria were established based on perception thresholds to evaluate habitability due to the effects of wind-induced building motion with a return period of one year: one criterion for office buildings and the other for residential buildings.

In the current study, the degradation of manual task performance is based on accuracy and is defined as a ratio of the mean resultant distances measured under a motion condition to the embedded static condition. For example, a ratio of 1.26 at 0.5 Hz 8 milli-g suggests that the task performance accuracy decreased by 26%. Contours can be extrapolated from the ratios determined for all motion conditions tested in the current study. Although some low acceleration (for example 8 milli-g at 0.125 Hz) motion used in the current study is considered to be satisfactory according to the ISO 10137:2007 (International Organization for Standardization, 2007), the low acceleration motion was found to decrease CTT accuracy by 15 to 26%. This suggests that using the criteria for building designs does not ensure that manual tasks are unaffected. Furthermore, the minimum acceleration that causes a measurable degradation in task performance is unknown. Further investigations are warranted to determine the minimum acceleration causing measurable task performance degradation.

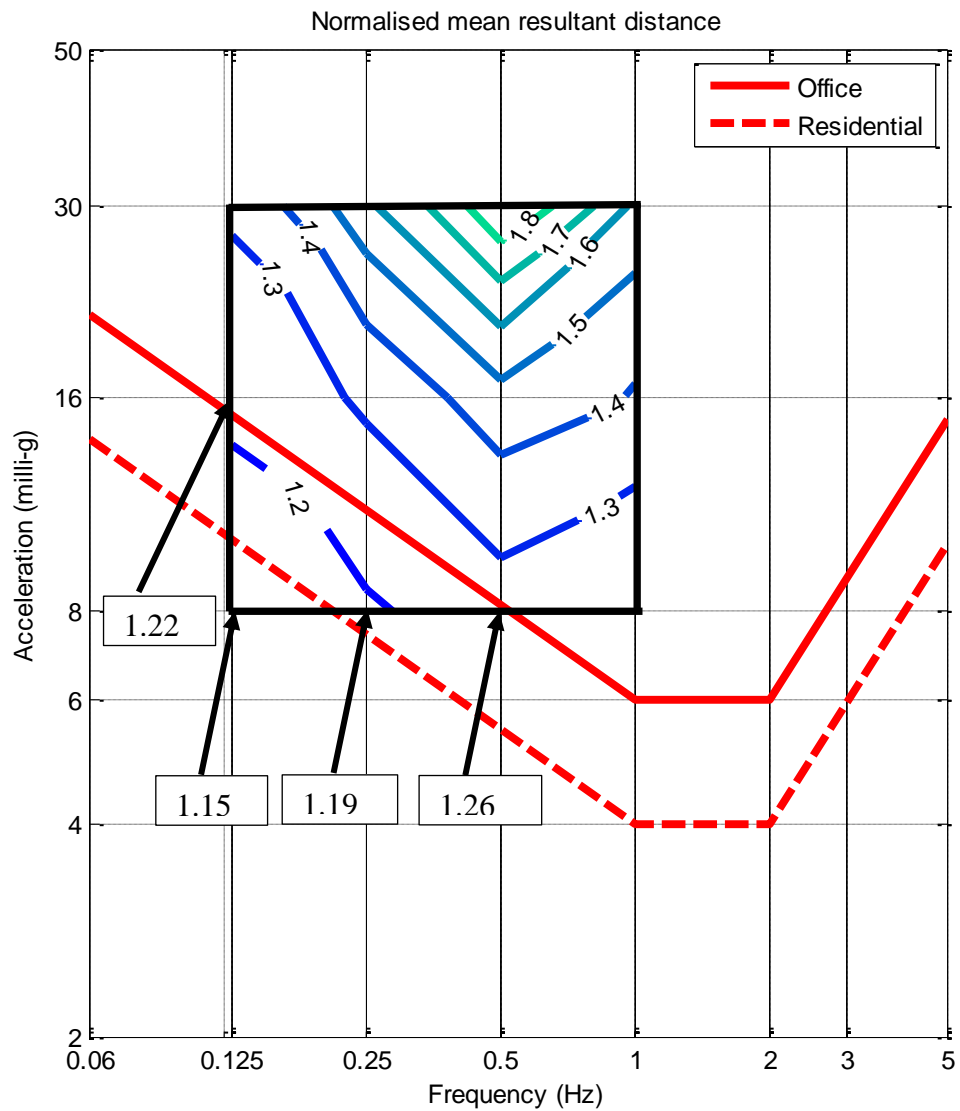


Figure 4.17. A comparison of manual task performance degradations against one-year return period acceleration design criteria (International Organization for Standardization, 2007). Numbers in boxes or on contour lines are ratios of CTT accuracy measured under a motion condition to static condition. The contours were extrapolated from the ratios determined for all motion conditions tested in the current study.

4.5.6 Effects of other factors on task performance

Results of this chapter show the average accuracy of CTT performance, that is, mean resultant distance, measured under the final and embedded static conditions are lower than that of the start-up static condition. This degradation in task performance under static condition over time is likely due to effects of other factors such as fatigue, boredom, or any other related natural causes over time associated with exposure to motion and/or performing the CTT.

Compared with the motion effects however, the contributions of other factors are smaller. The effect size of other factors is 0.42 (Cohen's d) while those of acceleration and frequency are 1.66 and 0.87 (Cohen's d) respectively. Although the effect size of other factors is small to moderate, it is smaller than the effect sizes of frequency and acceleration, as shown in Figure 4.18. Hence, the degradation in average accuracy, as observed here, is dominated by motion effects rather than other factors such as fatigue and boredom, or any other related natural causes over time caused by exposure to motion and/or performing the CTT.

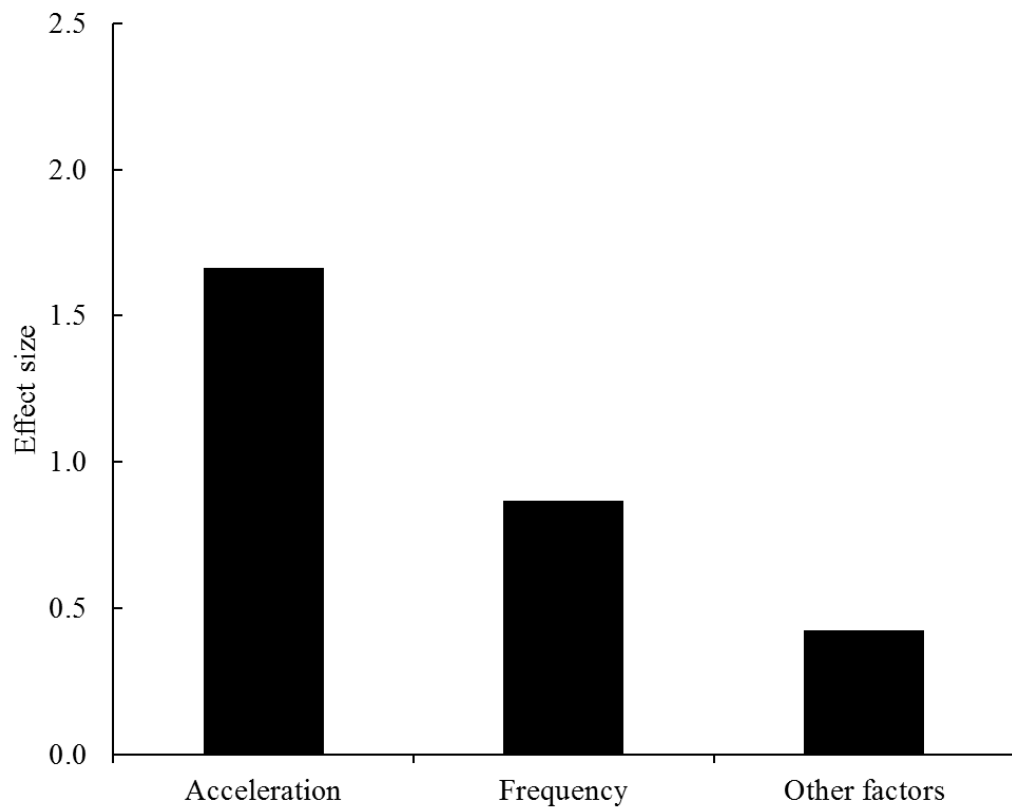


Figure 4.18. Effect sizes of acceleration, frequency, and other factors on mean resultant distance.

It has been shown that increases in the duration of exposure to high frequency (4 Hz), high acceleration (weighted RMS acceleration of 1.4 ms^{-2}) motion can degrade performance of the CTT (McLeod and Griffin, 1993). Regarding the acceptability of wind-induced building motion, the duration of exposure to motion is an important factor that precipitates nausea and task disruption (Burton et al., 2005). Prolonged exposure to wind-induced building motion can also cause discomfort, reduce concentration, trigger dizziness, headaches and nausea in office workers (Lamb et al., 2013, 2014). These symptoms can, in turn, affect task performance. Although participants in the current study were exposed to motion for a relatively short duration (approximately 30 minutes), \bar{r} , average accuracy of CTT performance, showed a tendency to decrease over time. This suggests that average accuracy, fluctuation, and/or maximum excursion of CTT performance may be further decreased with an increase in the duration of exposure.

4.5.7 Effect of gender and motion direction on task performance

It is well-known that perception thresholds of females are slightly lower than males (Kanda et al., 1988; Kojima et al., 1972; Tamura et al., 2006) and humans are slightly more sensitive to lateral motion than fore-aft under low frequency conditions (Kanda et al., 1988; Tamura et al., 2006). However, these studies also suggest that the effects of gender and motion direction are negligible in comparison with individual differences. This chapter has shown that the effects of gender and motion direction are not significant, which lends support to the conclusions of previous research (Kanda et al., 1988; Tamura et al., 2006).

4.6 Limitations

Manual tasks carried out in buildings are likely to differ from the CTT used in the current study, in terms of task difficulty, occupant posture, and the dexterity required to undertake the task. Results of this chapter may not be directly applicable to other types of manual tasks undertaken in buildings, such as sitting at a desk and working on a computer. Future research is required to investigate the extent to which these findings are applicable to other types of manual tasks that typically occur in offices.

Sinusoidal motion was used to simulate a short period (64 seconds) of wind-induced building motion that contained multiple cycles of relatively similar amplitude, to replicate motion that occurs in a typical burst of wind-induced building motion. The current study did not therefore investigate the effects of a sudden change in the motion amplitude of random or high peak factor random wind-induced building motion. Future studies are warranted to consider the effects of random motion on manual task performance.

The participants were all young, healthy and fit university students with a mean age of 21 years, which is much lower than the mean age of the general population. Hence the observed effects of motion on manual task performance may not be representative for the general population.

4.7 Conclusions

Few studies have investigated the effects of low-frequency, low-acceleration motion on manual task performance and the studies have reported inconclusive findings. Furthermore, none of these past studies established relationships between manual task performance with motion frequency and acceleration magnitudes, nor determined the potential causes that affected manual task performance. While Goto et al. (1990) quantitatively found that low-frequency, low-acceleration motion could degrade manual task performance, other studies found neutral conclusions (for example Burton et al., 2011; Jeary et al., 1988). This chapter has presented the results of a series of motion simulator studies that used a CTT as a paradigm to investigate the effects of motion on manual task performance.

Results of this chapter show that low-frequency, low-acceleration motion causes a large and significant degradation in manual task performance, measured by quantifying the accuracy of laser pointing on a small target. Motion acceleration and frequency each contributed to causing the observed performance degradations, but the effects of acceleration were significantly greater than the effects of frequency.

Acceleration shows a strong inverse relationship with task performance, with large performance degradations occurring even at the lowest test acceleration of 8 milli-g. The acceleration effect is attributable to an increase in inertial force, which can induce visual impairment, disrupt balance, increase vibration breakthrough, and trigger motion sickness and/or sopite syndrome. Evidently, sopite syndrome, a mild form of motion sickness, contributed significantly to the observed manual task performance degradation. This aspect of the study is presented in the following chapter.

The effect of frequency is associated with the frequency response characteristic of the human body that increases body sway as motion approaches the resonant frequency of a standing human, which occurs at near 0.5 Hz. The interaction of acceleration and frequency further degraded task performance, which can cause discomfort, divert attention resources from performing a manual task, and trigger anxiety that increases the difficulty to response to a manual task.

The current criteria or recommendations do not consider the effects of wind-induced building motion on manual task performance in buildings used by the general population (for example International Organization for Standardization, 2007). Results of this chapter suggest that using the criteria to assess the performance of wind-excited buildings does not ensure the performance of manual tasks is unaffected.

Other factors such as fatigue, boredom, and other natural causes over time induced by exposure to motion and/or performing the CTT also degrade task performance. However, the contribution of these factors to the degradation in manual task performance is significantly less than that of frequency, acceleration, and their interaction. Compared with individual difference, the effects of gender and motion direction on manual task performance are minor and negligible.

CHAPTER 5

EFFECTS OF SOPITE SYNDROME ON A CONTINUOUS TRACKING TASK PERFORMED UNDER LOW-FREQUENCY, LOW-ACCELERATION MOTION CONDITIONS

5.1 Introduction

Chapter 4 has shown that low-frequency, low-acceleration motion degrades performance in a continuous tracking task (CTT). The mechanisms causing the degradation are unclear. This degradation is thought to be due to motion sickness, visual impairment, disruption on balance, increase in vibration breakthrough and/or a combination of these factors.

A majority of previous studies suggest that wind-induced building motion may provoke salient symptoms of motion sickness, such as nausea and vomiting (for example Burton et al., 2005; Goto, 1983; Hansen et al., 1973). However, the presentation of salient symptoms of motion sickness is likely to occur at high acceleration magnitudes that are more relevant to extreme windstorms. Recent studies suggest that wind-induced building motion at low acceleration magnitudes, which occur more frequently than extreme windstorms, may provoke low-dose motion sickness symptoms such as tiredness, low motivation, distraction from work activities, and low mood for a significant number of building occupants (Lamb et al., 2013, 2014; Walton et al., 2011). These symptoms centre around drowsiness and/or mood change were believed to be associated with sopite syndrome caused by exposing healthy individuals to motion (Graybiel and Knepton, 1976; Matsangas and McCauley, 2014). Furthermore, Lamb et al. (2014) found that subjective work performance and cognitive performance decreased as the severity of sopite syndrome increased. This suggests that motion-induced sopite syndrome may have a measurable effect on manual task performance, making this worthy of further investigation to advance our understanding of human responses to wind-induced building motion.

This chapter investigates the incidence of sopite syndrome under low-frequency, low-acceleration motion conditions. If sopite syndrome is found to occur under low-frequency, low-acceleration motion conditions, further analyses will be undertaken to determine the effects of sopite syndrome on manual task performance. It is postulated that i) exposure to low-frequency, low-acceleration motion increases the severity of sopite syndrome; and ii) manual task performance decreases with any increase in sopite syndrome severity.

5.2 Methodology

The results presented in this chapter were derived from data collected from the motion simulator experiment described in Chapter 3. Twenty participants were tested under fore-aft motion conditions and another 20 were tested under lateral motion conditions. Three acceleration magnitudes (8, 16, and 30 milli-g) and four frequencies (0.125, 0.25, 0.5, and 1 Hz) were used to produce 12 motion conditions. These acceleration and frequency ranges are comparable to those likely to occur in buildings undergoing wind-induced motion. The motion simulator experiment used a continuous tracking task (CTT) as a paradigm to investigate the effects of motion on manual task performance. The CTT required participants to hold a laser pointer and aim a laser light dot as close as possible to the centre of a target. Manual task performance was quantified by measuring the resultant distance between the laser light dot and the centre of the target. The severity of symptoms of motion sickness, in particular sopite syndrome, were measured at the beginning of the experiment, before exposure to any motion conditions, and at the end, after exposure to all motion conditions, using a Motion Sickness Assessment Questionnaire (MSAQ), as shown in Appendix B (Gianaros et al., 2001). If increases in severity of motion sickness symptoms were significant, the increases in motion sickness symptom severity will then be correlated with performance of the CTT. Other details of the experiment are presented in Chapter 3.

5.3 Analysis

5.3.1 *Changes in motion sickness scores due to exposure to low-frequency, low-acceleration motion*

Changes in motion sickness severity were examined based on MSAQ overall motion sickness score and subscale scores (see Section 3.4.4 and Appendix B), including sopite-related, central, gastrointestinal, and peripheral. Changes in overall motion sickness score and subscale scores were calculated by subtracting the pre-test score from the post-test score using Equation 5.1 and Equation 5.2 respectively.

Equation 5.1

Change in overall motion sickness score (%) = Post-test overall motion sickness score (%) – Pre-test overall motion sickness score (%)

Equation 5.2

Change in subscale score (%) = Post-test subscale score (%) – Pre-test subscale score (%)

One-way repeated-measures Analysis of Variance Analyses (ANOVAs) analysed whether there were any significant increases in overall motion sickness score and/or subscale scores. If the increases in overall motion sickness scores and/or subscale scores were significant, mixed-design two-way ANOVAs were used to investigate effects of motion direction and gender separately. In the mixed-design two-way ANOVAs, the pre-post-test condition was within-subjects factor and either motion direction or gender was the between-subjects factor.

5.3.2 Grouping of participants in accordance with changes in motion sickness scores

Section 4.4.4.4 has shown that effects of motion direction are not significant on CTT performance, therefore, in this Chapter, CTT performance of the two direction groups of 20 participants were combined to investigate the effects of motion sickness symptom severity on CTT performance. Where significant increases in MSAQ overall motion sickness score and/or any other subscale scores were found, participants were grouped in accordance with the corresponding changes in motion sickness scores. For example, if a significant increase was found in the changes in overall motion sickness score, the 40 participants were grouped into three groups (high, medium, and low) with approximately equal sample sizes in accordance with the changes in the overall motion sickness score. The number of participants in each group was approximately 13 with each group representing a severity level of overall motion sickness or a severity level of motion sickness subscale.

5.3.3 Effects of motion sickness on CTT performance under motion conditions

Mixed-design three-way ANOVAs with frequency and acceleration as within-subjects factors and severity level as between-subjects factor, and either mean (\bar{r}), standard deviation (σ_r), or maximum (\hat{r}) resultant distances as the dependent measure were used to assess motion sickness. The \bar{r} , σ_r , and \hat{r} respectively represent the average CTT performance, fluctuation, and maximum excursion of CTT performance, as discussed in Chapter 4.

5.4 Results

5.4.1 Effects of exposure to low-frequency, low-acceleration motion on changes in MSAQ overall motion sickness and subscale scores

A one-way repeated-measures ANOVA indicated an increase in MSAQ overall motion sickness scores from pre-test ($M = 16.98$, $SD = 7.14$) to post-test ($M = 21.77$, $SD = 12.55$) as significant, $F(1, 39) = 6.80$, $p\text{-value} = 0.013$. This represents an overall increase in motion sickness, with a moderate effect size of 0.47 (Cohen's d).

Importantly, significant increases were also found in sopite-related subscale scores, $F(1, 39) = 18.4$, $p\text{-value} < 0.001$, and central subscale scores, $F(1, 39) = 11.93$, $p\text{-value} = 0.001$. However, exposure to low-frequency, low-acceleration motion causes neither a significant increase in the peripheral subscale score, $F(1, 39) = 0.789$, $p\text{-value} = 0.38$ nor in gastrointestinal subscale scores, $F(1, 39) = 3.66$, $p\text{-value} = 0.063$. Changes of mean and standard deviation of all subscale scores are summarised in Table 5.1.

Table 5.1. Changes of mean and standard deviation of all subscale scores due to exposure to low-frequency, low-acceleration motion.

	Mean (%)		Standard deviation (%)		<i>p-value</i>
	Pre-test	Post-test	Pre-test	Post-test	
Sopite-related	18.47	27.57	9.59	16.2	< 0.001
Central	15.17	21.61	6.1	12.98	0.001
Gastrointestinal	14.72	18.33	6.27	12.59	0.063
Peripheral	21.02	18.89	11.26	13.57	0.38

The four MSAQ subscales show different patterns for the change scores, as shown in Figure 5.1. The largest increase was observed for the sopite-related subscale, with a moderate to large effect size of 0.68 (Cohen's d), followed by the central nervous system subscale with an effect size of 0.64 (Cohen's d). Exposure to low-frequency, low-acceleration motion increased the sopite-related and central nervous system symptom severity by 0.68 and 0.64 standard deviations respectively. Seventy percent of participants ($N = 28$) reported an increase in sopite-related subscale scores and 57.5 percent of participants ($N = 23$) reported increases in central subscale scores.

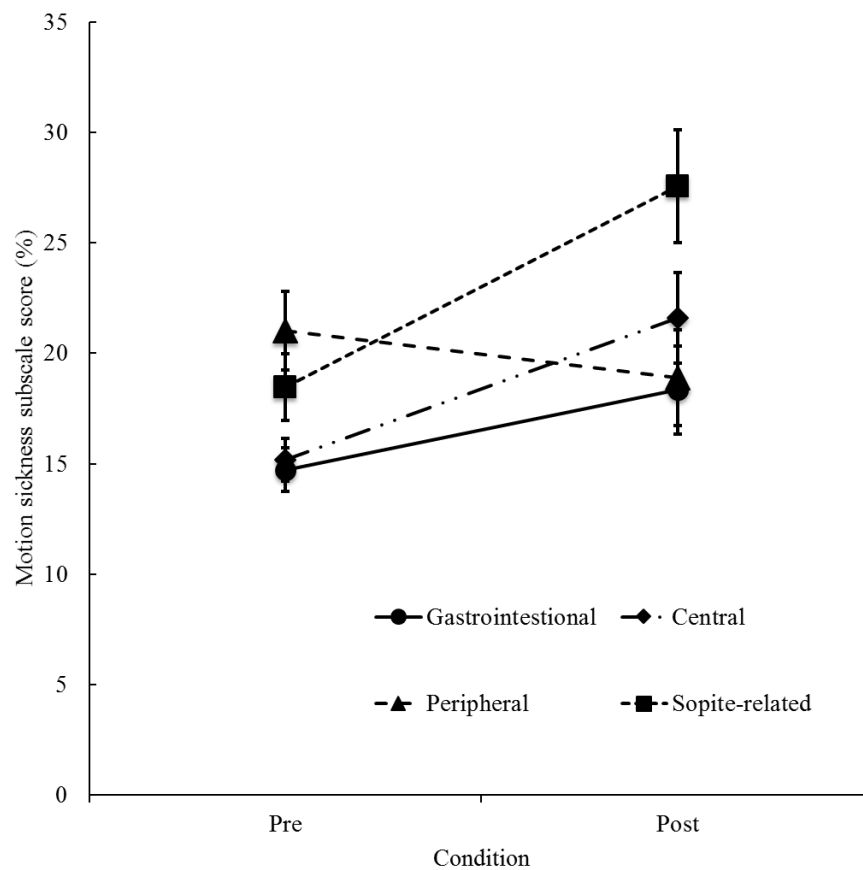


Figure 5.1. MSAQ subscale scores (mean \pm S.E.) pre- and post- exposure to motion of all participants ($N = 40$).

5.4.2 Effects of motion direction on changes in MSAQ overall motion sickness and subscale scores

Mixed-design, two-way ANOVAs were conducted with either the overall motion sickness score, sopite-related, or central subscale as the dependent measure, scores pre-post-test condition as the within-subjects factor and motion direction as the between-subjects factor. The mixed-design two-way ANOVAs indicated that motion direction had no significant effect on change in the overall motion sickness score, $F(1, 38) = 0.51$, $p\text{-value} = 0.48$, sopite-related, $F(1, 38) = 0.391$, $p\text{-value} = 0.536$, and central, $F(1, 38) = 1.78$, $p\text{-value} = 0.190$, subscale scores. Since increases in the gastrointestinal and peripheral subscale scores were not significant, and no statistical analysis was conducted for the effects of motion direction for gastrointestinal and peripheral subscale scores.

5.4.3 Effects of gender on changes in MSAQ overall motion sickness and subscale scores

Mixed-design two-way ANOVAs were conducted with either the overall motion sickness score, sopite-related, or central subscale scores as the dependent measure, pre-post-test condition as the within-subjects factor and gender as the between-subjects factor. The mixed-design two-way ANOVAs indicated that gender had no significant effect on change in the overall motion sickness score, $F(1, 38) = 0.47$, $p\text{-value} = 0.50$, sopite-related, $F(1, 38) = 0.129$, $p\text{-value} = 0.722$, and central, $F(1, 38) = 0.650$, $p\text{-value} = 0.425$, subscale scores. Since exposure to motion did not cause significant increases in the gastrointestinal and peripheral subscale scores, no statistical analysis was conducted for the effects of gender.

5.4.4 Grouping of participants based on sopite relate subscale score

As significant increases were found in sopite-related and central subscale scores, but not in the gastrointestinal and peripheral subscale scores, the following analyses explored the effects of symptoms of sopite syndrome and the central subscale on CTT performance. Results of this chapter show that 70% of participants ($N = 28$) reported increases on the sopite-related subscale score, as shown in Appendix C. Based on these increases in sopite-related subscale scores, participants were grouped into three groups (high, medium, and low sopite syndrome severity groups), as shown in Figure 5.2.

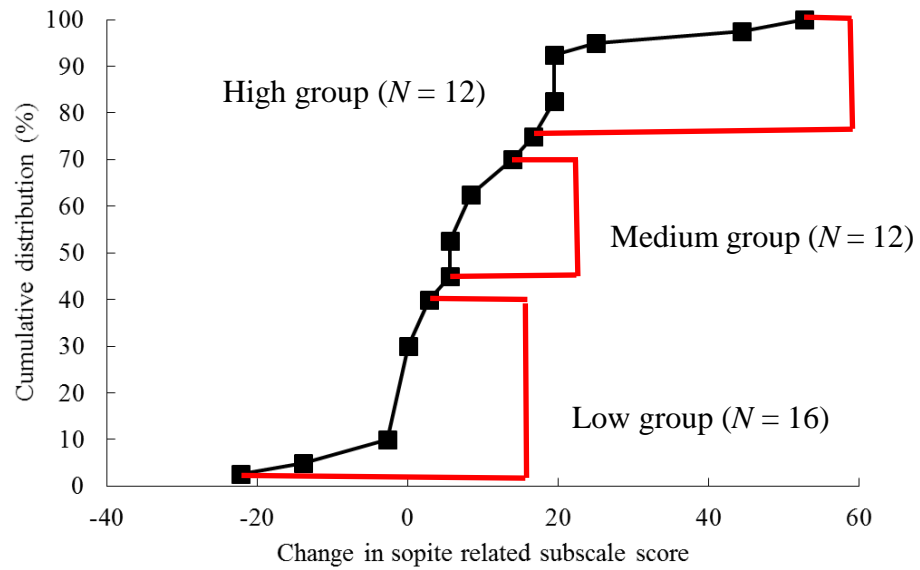


Figure 5.2. Cumulative frequency distribution of change in sopite-related subscale score.

A mixed-design two-way ANOVA with changes in the sopite-related subscale score pre-post-test condition as within-subjects factor and participant's sopite syndrome severity as a between-subjects factor highlighted significant differences in the sopite-related subscale score between sopite syndrome severity groups, $F(2, 37) = 9.818$, $p\text{-value} < 0.001$, as shown in Figure 5.3. Participants in the high sopite syndrome severity group suffered more severe sopite syndrome than the medium and low groups. This result lead to question whether the difference in task performance between the sopite syndrome severity groups was significant.

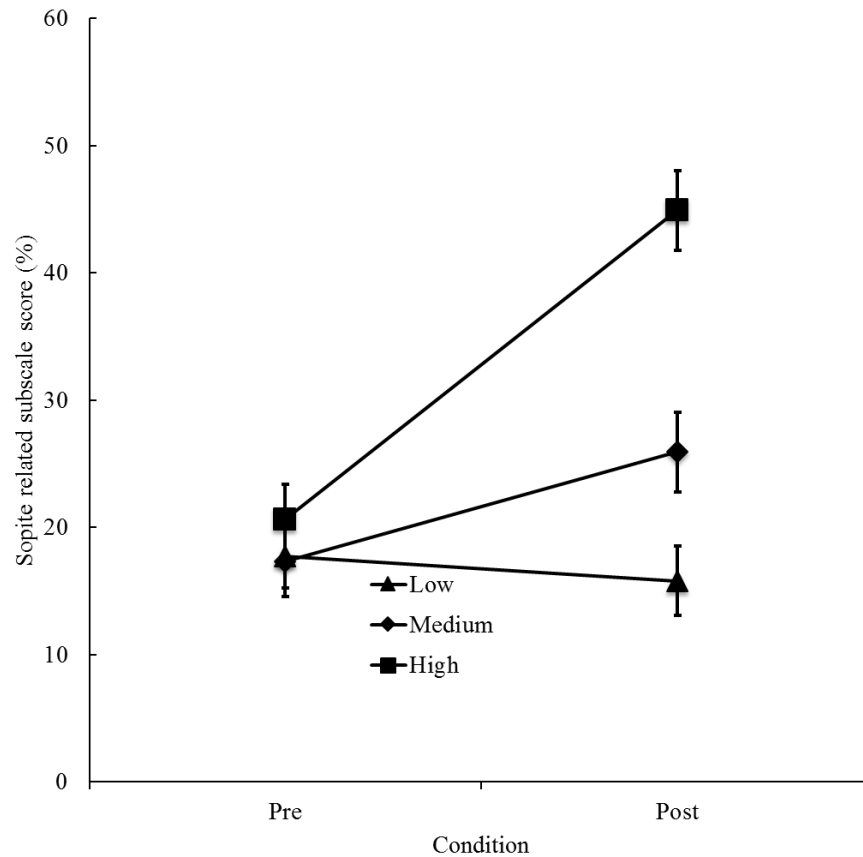


Figure 5.3. Changes in sopite-related subscale scores (mean \pm S.E.) across high ($N = 12$), medium ($N = 12$), and low ($N = 16$) sopite syndrome severity groups.

5.4.5 Effects of sopite-related subscale score on mean resultant distance – average CTT performance

A mixed-design three-way ANOVA with frequency and acceleration as within-subjects factors and sopite-related score level as the between-subjects factor showed that effects of sopite syndrome severity on the mean resultant distance (\bar{r}), that is, average CTT performance, $F(2, 37) = 4.35$, $p\text{-value} = 0.020$, were significant. Decreases in average CTT performance were significant as sopite syndrome severity increased from the low ($N = 16$) to high ($N = 12$) groups, as shown in Figure 5.4. The decrease in average CTT performance from the low to high sopite syndrome severity groups is equal to an effect size of 1.11 (Cohen's d). The mean and standard deviation of average CTT performance of all the sopite syndrome groups are summarised in Table 5.2.

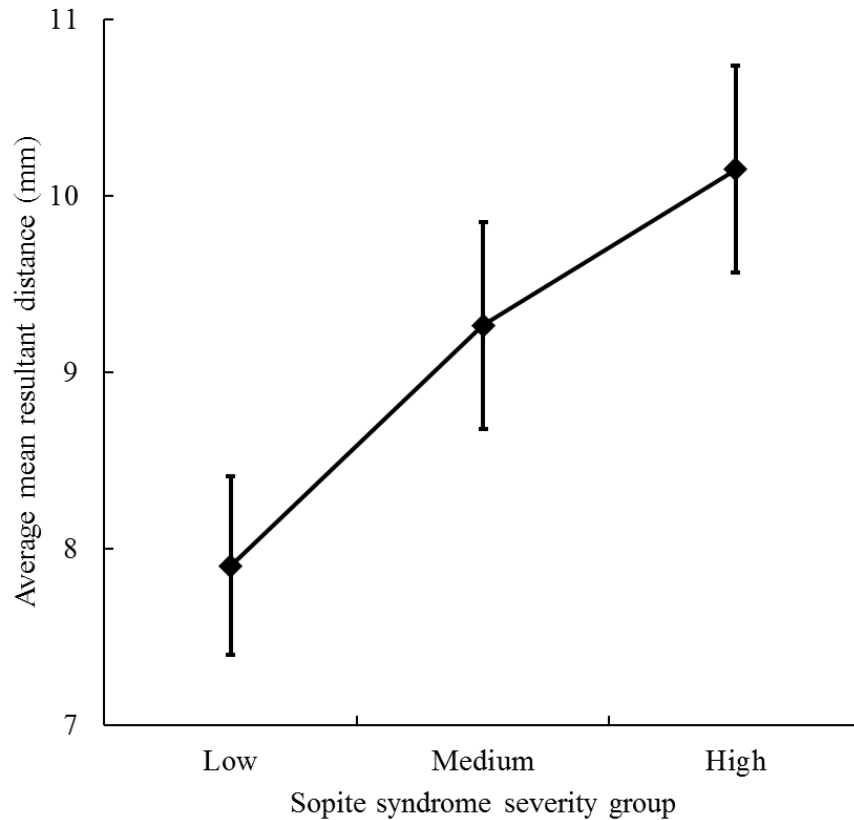


Figure 5.4. Average mean resultant distance (mean \pm S.E.) across high ($N = 12$), medium ($N = 12$), and low ($N = 16$) sopite syndrome severity groups.

Table 5.2. Mean and standard deviation of average CTT performance of the low, medium, and high sopite syndrome groups.

Sopite syndrome severity	Mean (mm)	Standard deviation (mm)
Low ($N = 16$)	7.90	2.032
Medium ($N = 12$)	9.26	2.030
High ($N = 12$)	10.15	2.030

The mixed-design three-way ANOVA showed that effects of both frequency, $F(3, 111) = 33.4$, $p\text{-value} < 0.001$, and acceleration, $F(2, 74) = 112.4$, $p\text{-value} < 0.001$, on average CTT performance were significant. Figure 5.5 and Figure 5.6 show that participants in the high sopite syndrome group performed consistently worse across all levels of frequency and acceleration than the low and medium groups. Furthermore, the average CTT performance of all sopite syndrome groups exhibited comparable nonlinear characteristics across frequency and monotonically increased across accelerations.

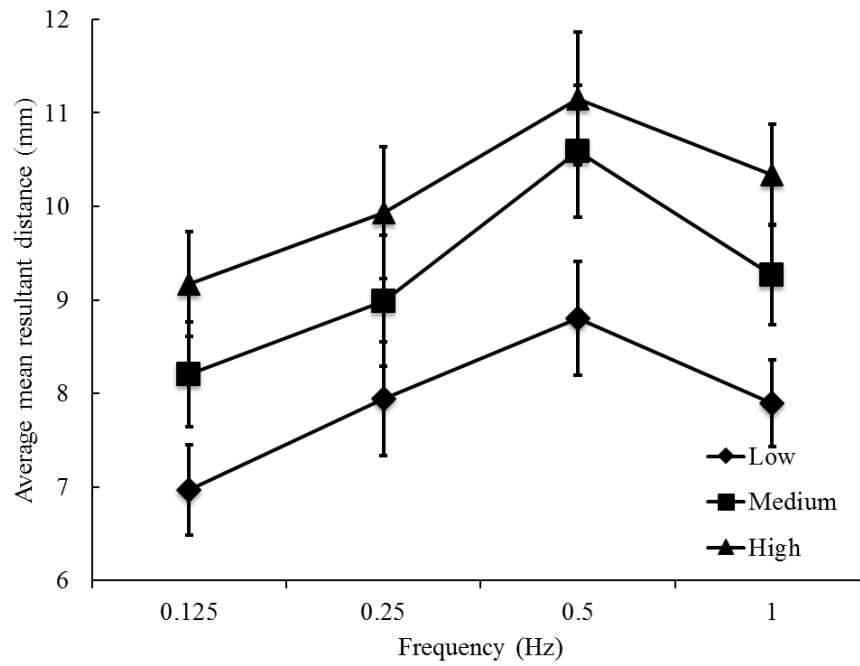


Figure 5.5. Average mean resultant distance (mean \pm S.E.) across frequency grouped by sopite syndrome severity: high ($N = 12$), medium ($N = 12$), and low ($N = 16$).

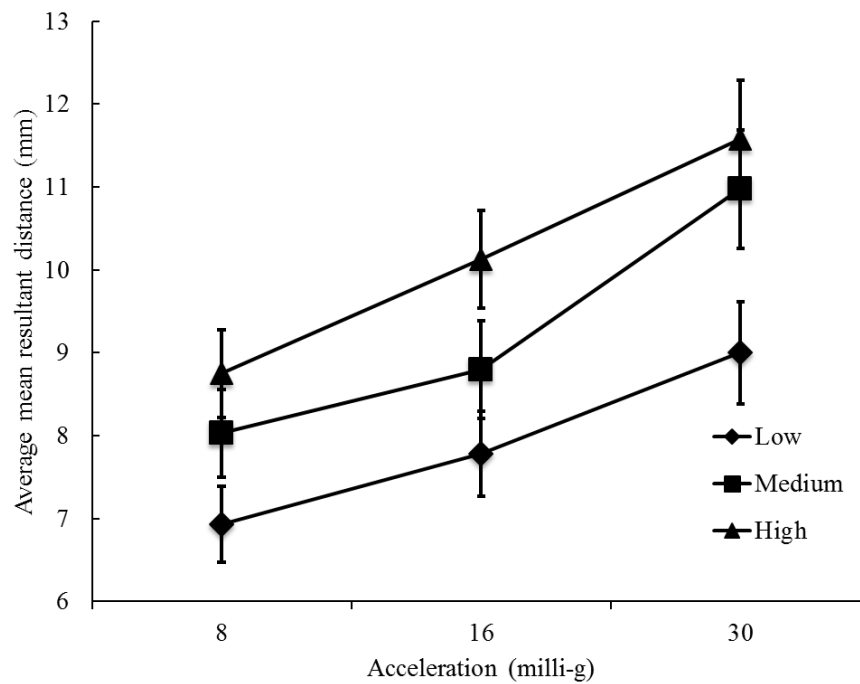


Figure 5.6. Average mean resultant distance (mean \pm S.E.) across acceleration, grouped by sopite syndrome severity: high ($N = 12$), medium ($N = 12$), and low ($N = 16$).

5.4.6 Effects of sopite-related subscale score on standard deviation resultant distance – fluctuation of CTT performance

A mixed-design three-way ANOVA showed significant differences in standard deviation resultant distance (σ_r), that is, fluctuations of CTT performance between sopite syndrome groups, $F(2, 37) = 4.66$, $p\text{-value} = 0.016$, as shown in Figure 5.7. In the mixed-design three-way ANOVA, frequency and acceleration were within-subjects factors and sopite syndrome group was the between-subjects factor, and σ_r was the dependent measure. Table 5.3 summarises the mean and standard deviation of σ_r of the low, medium, and high sopite syndrome groups. The increase in σ_r is equal to an effect size of 1.09 (Cohen's d), comparing the low against the high sopite syndrome groups.

Table 5.3. Mean and standard deviation of fluctuation of CTT performance of the low, medium, and high sopite syndrome groups.

Sopite syndrome severity	Mean (mm)	Standard deviation (mm)
Low ($N = 16$)	4.57	1.236
Medium ($N = 12$)	5.61	1.233
High ($N = 12$)	5.91	1.233

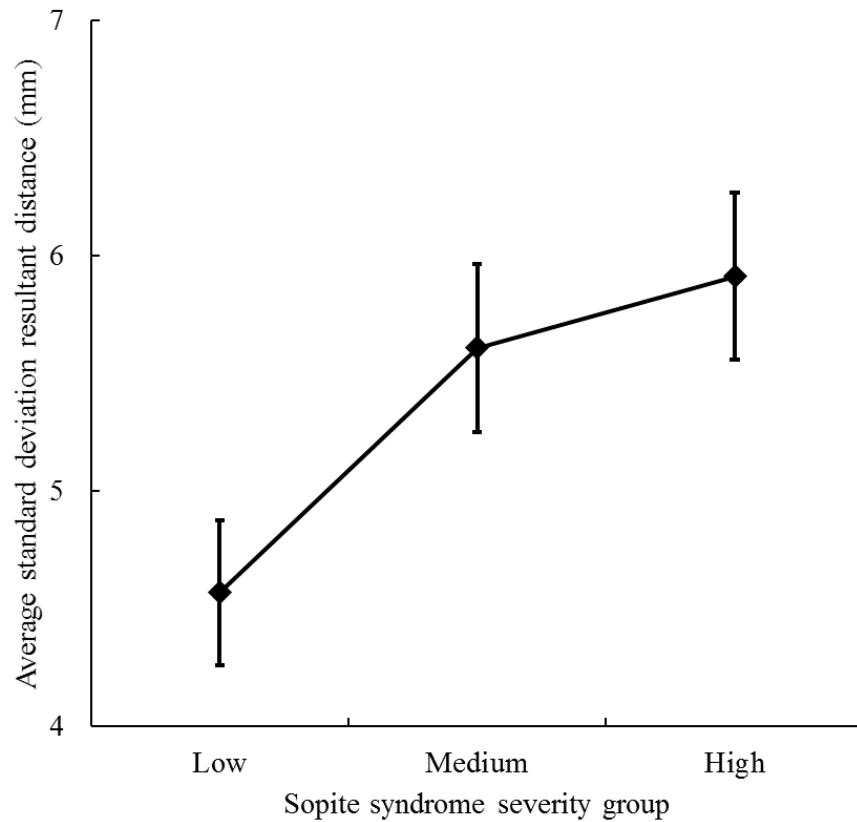


Figure 5.7. Average standard deviation resultant distance (mean \pm S.E.) across high ($N = 12$), medium ($N = 12$), and low ($N = 16$) sopite syndrome severity groups.

The mixed-design three-way ANOVA also showed that main effects of both frequency, $F(3, 111) = 19.09, p\text{-value} < 0.001$, and acceleration, $F(2, 74) = 57.4, p\text{-value} < 0.001$, were significant on the fluctuation of CTT performance. In addition, participants in the high sopite syndrome group performed consistently worse across all levels of frequency and acceleration than the low sopite syndrome group, as shown in Figure 5.8 and Figure 5.9 respectively.

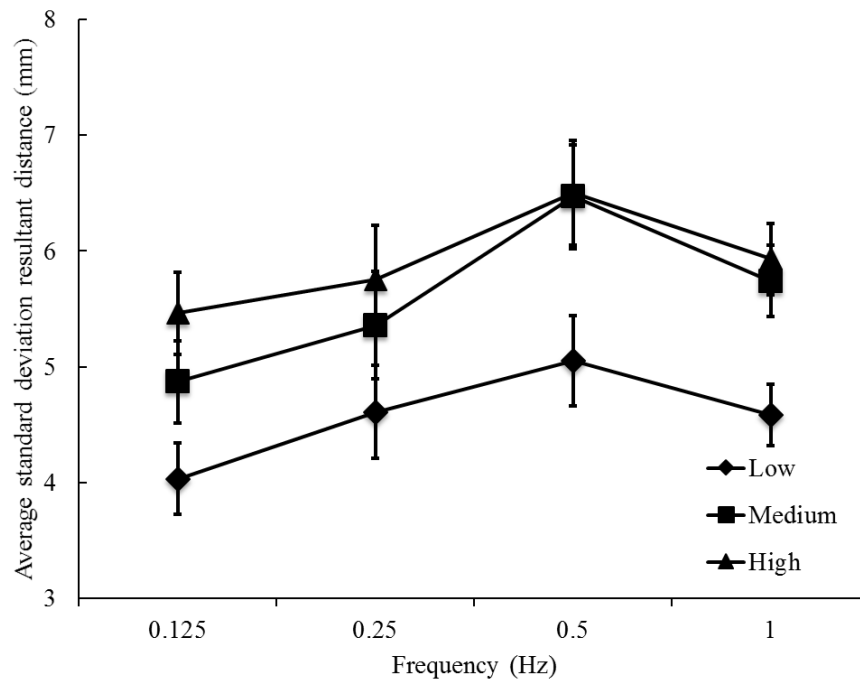


Figure 5.8. Average standard deviation resultant distance (mean \pm S.E.) across frequency grouped by sopite syndrome severity: high ($N = 12$), medium ($N = 12$), and low ($N = 16$).

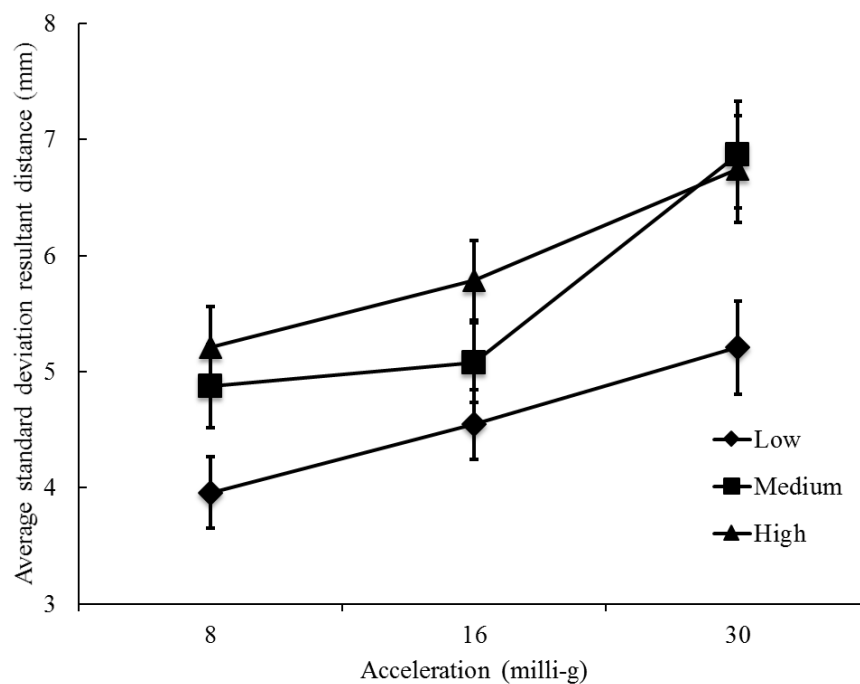


Figure 5.9. Average standard deviation resultant distance (mean \pm S.E.) across acceleration grouped by sopite syndrome severity: high ($N = 12$), medium ($N = 12$), and low ($N = 16$).

5.4.7 Effects of sopite-related subscale score on maximum resultant distance – maximum excursion of CTT performance

Figure 5.10 shows that the maximum excursion of CTT performance increased with increases in sopite syndrome severity. A mixed-design three-way ANOVA with frequency and acceleration as within-subjects factors and sopite syndrome group as the between-subjects factor shows that the effects of sopite syndrome severity level on the maximum excursion of CTT performance, $F(2, 37) = 4.45$, $p\text{-value} = 0.019$ were significant. The mean and standard deviation of the maximum excursion of CTT performance are summarised in Table 5.4. The difference of the maximum excursion of CTT performance between the low and high sopite syndrome groups is equal to an effect size of 1.08 (Cohen's d).

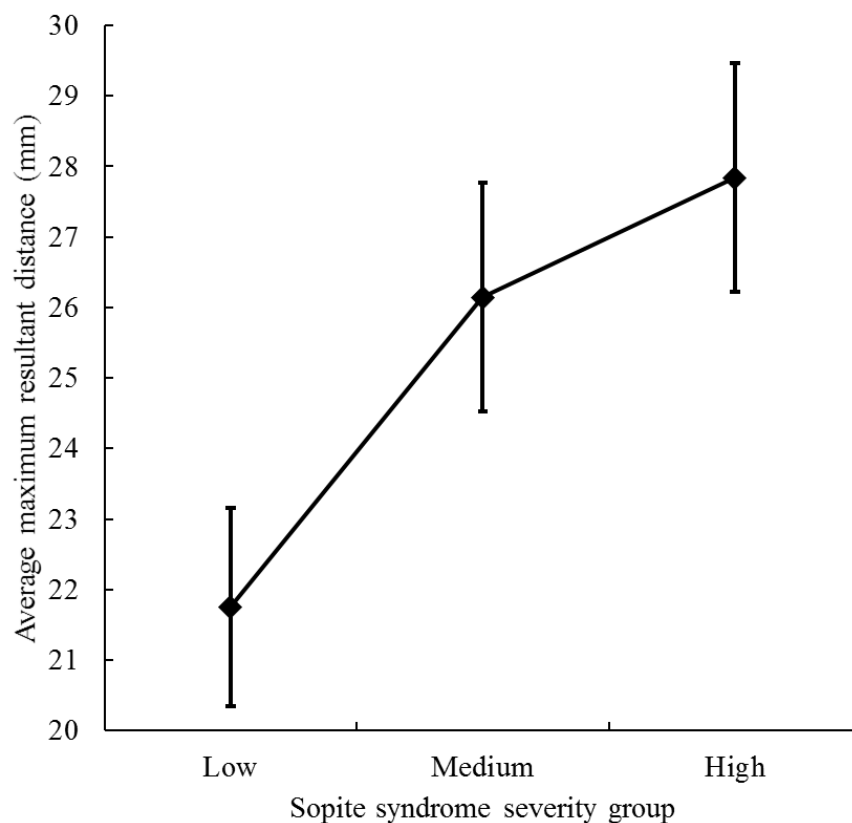


Figure 5.10. Average maximum resultant distance (mean \pm S.E.) across high ($N = 12$), medium ($N = 12$), and low ($N = 16$) sopite syndrome severity groups.

Table 5.4. Mean and standard deviation of maximum excursion of CTT performance of the low, medium, and high sopite syndrome groups.

Sopite syndrome severity	Mean (mm)	Standard deviation (mm)
Low ($N = 16$)	21.756	5.616
Medium ($N = 12$)	26.145	5.615
High ($N = 12$)	27.842	5.615

Effects of both frequency, $F(3, 111) = 25.809$, $p\text{-value} < 0.001$, and acceleration, $F(2, 74) = 77.125$, $p\text{-value} < 0.001$, on maximum excursion of CTT performance were significant. Figure 5.11 and Figure 5.12 show that the maximum excursion of CTT performance of the high sopite syndrome group performed consistently worse across all levels of frequency and acceleration than the low group.

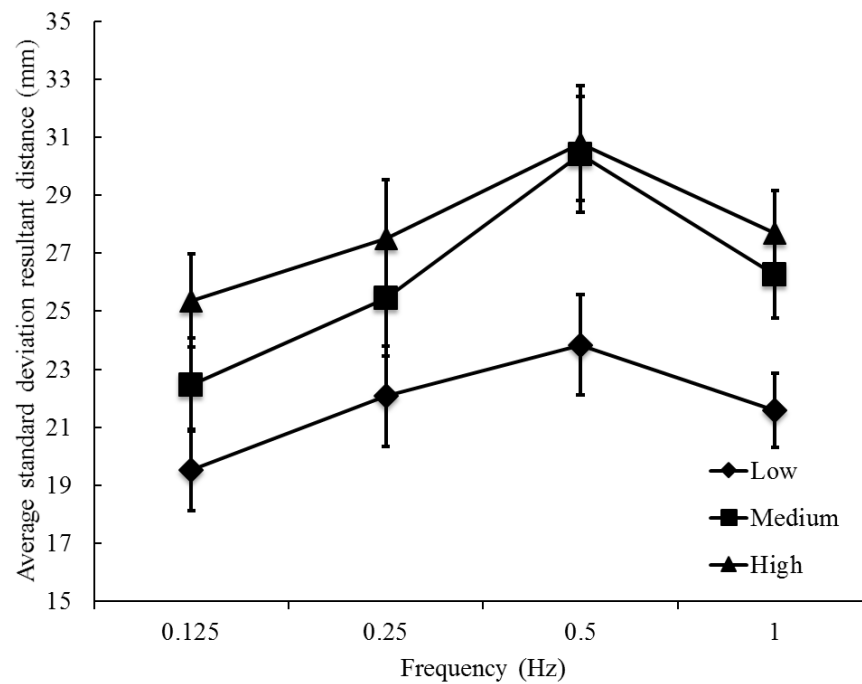


Figure 5.11. Average maximum resultant distance (mean \pm S.E.) across frequency grouped by sopite syndrome severity: high ($N = 12$), medium ($N = 12$), and low ($N = 16$).

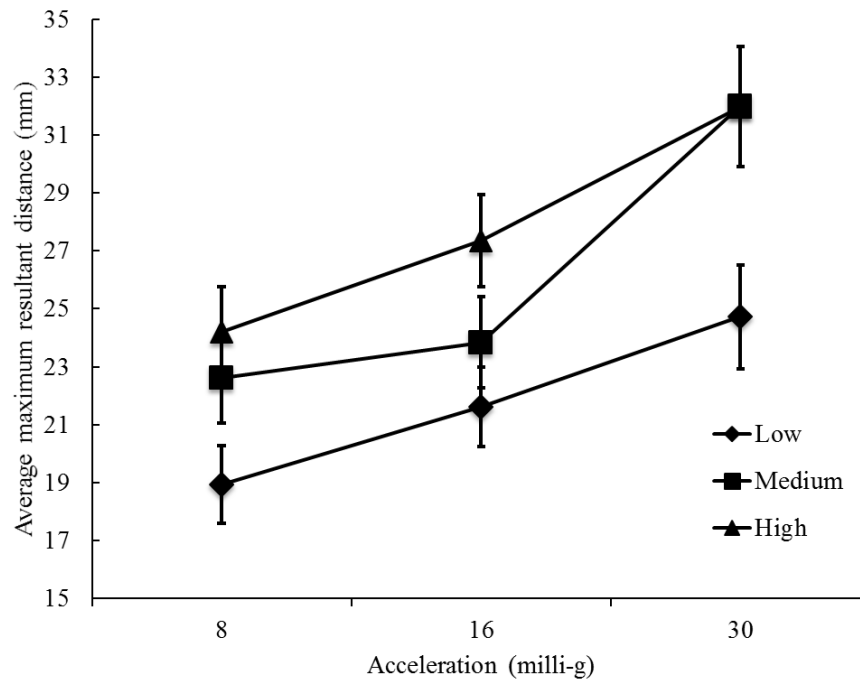


Figure 5.12. Average maximum resultant distance (mean \pm S.E.) across acceleration grouped by sopite syndrome severity: high ($N = 12$), medium ($N = 12$), and low ($N = 16$).

5.4.8 Grouping of participants based on central subscale score

Of the participants, 57.5 percent ($N = 23$) reported increases in the central subscale score, as shown in Appendix C. Based on the increase in the central subscale score, participants were separated into the low, medium, and high central severity groups with sample sizes of 17, 10, and 13 respectively, as shown in Figure 5.13.

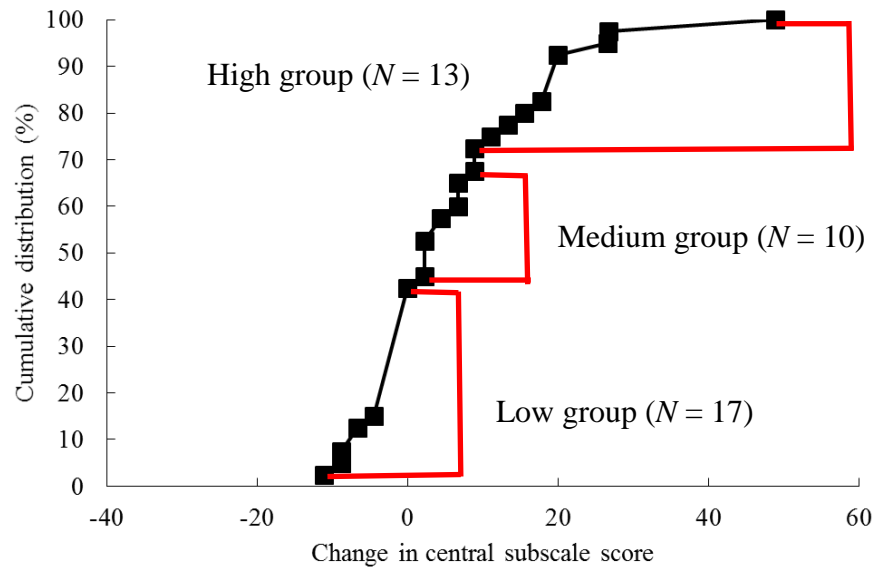


Figure 5.13. Cumulative frequency distribution of change in central subscale score.

Figure 5.14 shows that changes in the central subscale score of the high severity group are higher than those of medium and low severity groups. A mixed-design two-way ANOVA with pre-post-test condition as the within-subjects factor and participant's central symptoms severity groups as the between-subjects factor indicates that difference in the change in central subscale score between sopite syndrome severity groups were significant, $F(2, 37) = 8.628$, $p\text{-value} = 0.001$.

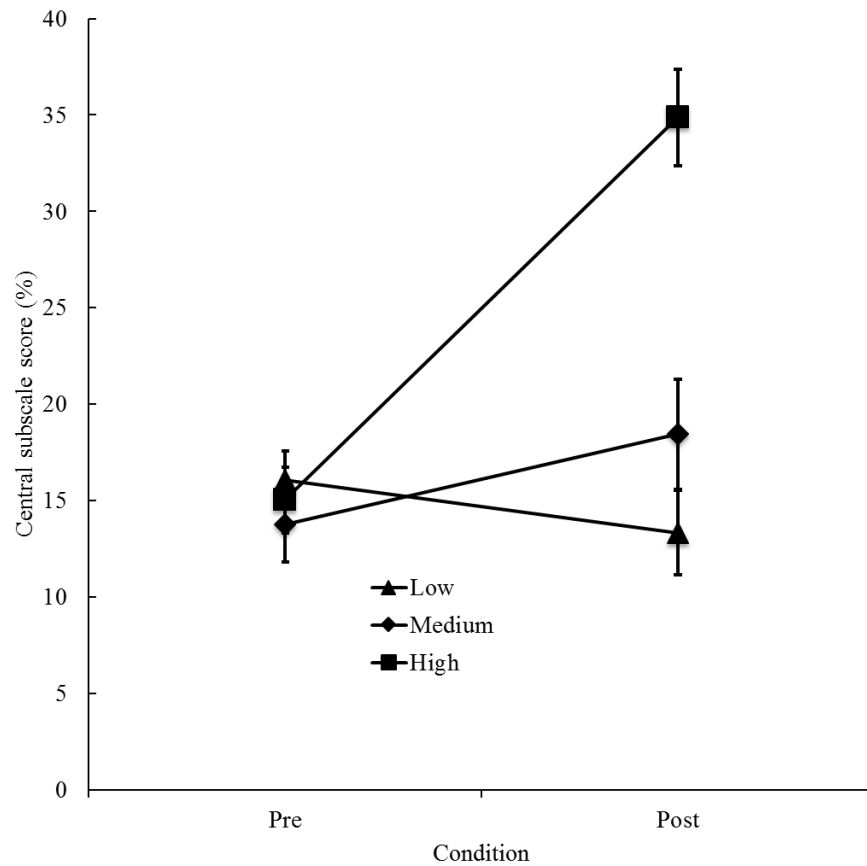


Figure 5.14. Change in central subscale score (mean \pm S.E.) across high ($N = 12$), medium ($N = 12$), and low ($N = 16$) sopite syndrome severity groups.

5.4.9 Effects of central subscale score on CTT performance under motion conditions

Mixed-design three-way ANOVAs indicated that the mean (\bar{r}), $F(2, 37) = 0.552$, $p\text{-value} = 0.580$, standard deviation (σ_r), $F(2, 37) = 0.394$, $p\text{-value} = 0.677$, and maximum (\hat{r}) resultant distances, $F(2, 37) = 0.422$, $p\text{-value} = 0.659$, between the central symptom severity groups had no significant difference. These results contrast to the effects of sopite syndrome on the CTT performance.

5.4.10 Participants who withdrew from the study due to severe motion sickness symptoms

Four participants (9% of the total sample) asked to terminate the experiment because they felt sick. Increases in the MSAQ overall motion sickness score of these participants from pre-test ($M = 14.9$, $SD = 3.67$) to post-test ($M = 50$, $SD = 27.5$) were significant, $F(1, 3) = 20.3$, $p\text{-value} = 0.02$. This shows an overall increase in motion sickness due to exposure to motion, with a large effect size of 1.79 (Cohen's d).

Significant increases were observed for the gastrointestinal subscale, $F(1, 3) = 10.8$, $p\text{-value} = 0.046$, and for the central nervous system subscale, $F(1, 3) = 26.7$, $p\text{-value} = 0.014$. No significant difference was observed for peripheral, $F(1, 3) = 8.82$, $p\text{-value} = 0.059$, nor for sopite syndrome subscales, $F(1, 3) = 7.30$, $p\text{-value} = 0.074$, as shown in Figure 5.15. The largest increase was observed for the central subscale, with a large effect size of 1.97 (Cohen's d), followed by the gastrointestinal subscale with a large effect size of 1.14 (Cohen's d).

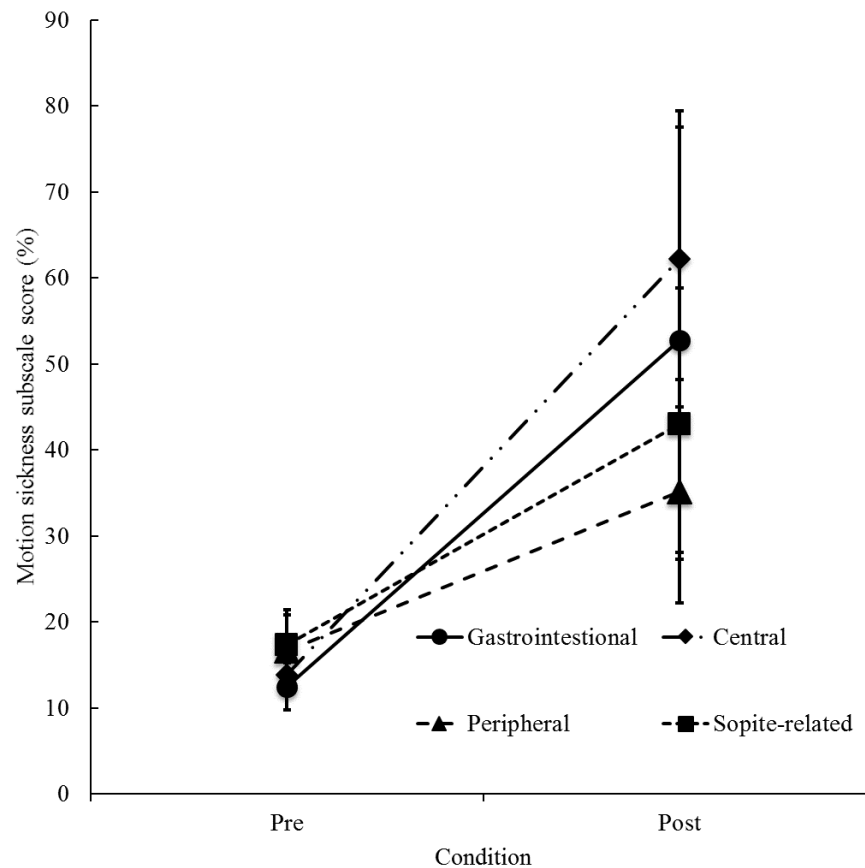


Figure 5.15. MSAQ subscale scores (mean \pm S.E.) of participants who withdrew from the lateral motion experiment ($N = 4$).

Table 5.5 shows the experimental condition the four participants experienced immediately before deciding to withdraw from the study. Each participant's CTT accuracy in this condition was compared with the average CTT accuracy of the main sample ($N = 40$) in the same condition. This shows that the CTT accuracy was on average 20% worse than for the main sample prior to withdrawing from the study. However, the sample size of four is too small for significance testing.

Table 5.5. Motion conditions and CTT accuracy immediately before withdrawing from the experiment; comparison of performance in the main sample measured under the same motion conditions.

Participant	Gender	Motion Direction	Motion condition		Individual CTT accuracy (mm)	Main sample average accuracy (mm)	Percentage difference (%)
			Frequency (Hz)	Acceleration (milli-g)			
1	Male	Lateral	0.25	16	7.6	8.6	-11
2	Female	Lateral	0.125	30	12.9	8.6	51
3	Female	Lateral	0.5	8	10.3	8.2	26
4	Female	Lateral	0.125	8	8.6	7.5	15
						Average	20.3

5.5 Discussion

5.5.1 Exposure to low-frequency, low-acceleration motion provokes sopite syndrome

The results of this chapter show that the combined influence of approximately 30 minutes exposure to motion across all conditions is sufficient to cause some form of motion sickness in most participants. A majority (approximately 70%) of the participants reported an increase in the sopite-related subscale score. Therefore, the participants were very likely to experience symptoms of mild motion sickness or sopite syndrome that included feeling annoyed or irritated, drowsy, tired or fatigued, and/or uneasy. Some previous studies have investigated incidence of sopite syndrome provoked by vehicular or apparent motion (for example Graybiel and Knepton, 1976; Lawson and Mead, 1998; Wright et al., 1995). However, little is known about incidence of sopite syndrome in wind-induced building environments. Recently, Lamb et al. (2014) suggested that motion sickness mostly manifested as symptoms of sopite syndrome, such as tiredness, low motivation, distraction from work activities, rather than salient symptoms of motion sickness, such as pallor, cold sweating, nausea, or vomiting. Results of this chapter, in a controlled laboratory environment, confirm that low-frequency, low-acceleration motion, comparable to wind-induced building motion, can provoke sopite syndrome.

Adverse effects of wind-induced building motion on habitability can have larger effects than some previous studies had thought. Before Walton et al. (2011), most studies focused on thresholds of perception to wind-induced building motion (for example Chen and Robertson, 1972; Tamura et al., 2006). Few studies reported occurrences of salient symptoms of motion sickness, such as pallor, cold sweating, nausea, or vomiting in real or simulated wind-excited building environments (for example, Burton et al., 2005; Goto, 1983; Hansen et al., 1973; Irwin and Goto, 1984). These studies generally considered these salient symptoms of motion sickness as major adverse effects on building occupants. Although they mentioned items such as difficulty in concentration, they were not aware of the appearance of sopite syndrome, let alone attempted to measure it. For example, Hansen et al. (1973) reported that an average of 41.3% of participants in two buildings felt motion sickness symptoms, including headaches, dizziness, queasiness, and nausea after experiencing five to six hours of perceptible wind-induced building motion. Goto (1983) reported that a typhoon that lasted for a few daylight hours induced building motion that affected 72.3% of the occupants physically or psychologically, including motion sickness, headache, anaemia, and stress.

Graybiel and Knepton (1976) indicated that sopite syndrome can occur before the appearance, or in the absence of, other salient symptoms of motion sickness. They stated that “the onset was insidious, and the unsophisticated might attribute the yawning and drowsiness to boredom and relaxation” (p. 876). Similarly, occupants in wind-excited buildings may not be aware that wind-induced building motion can provoke symptoms of sopite syndrome, such as tiredness, drowsiness, fatigue, and a disinclination to undertake physical and/or mental work. The occupants may misattribute symptoms of sopite syndrome to work and/or other daily activities (Walton et al., 2011). More importantly, sopite syndrome can occur more frequently and cause larger adverse effects on building occupants than other salient symptoms of motion sickness.

5.5.2 Effects of sopite syndrome on task performance

Chapter 4 clearly shows that low-frequency, low-acceleration motion degrades task performance with participants performing worse as acceleration increased. Furthermore, a nonlinear relationship exists between task performance and motion frequency. The results presented in this chapter show that there is a strong inverse relationship between measures of sopite syndrome and CTT performance under motion conditions; task performance decreases with increases in sopite syndrome severity. The relationships between task performance and frequency and acceleration remained essentially unchanged for the three sopite syndrome groups: high, medium, and low sopite syndrome severity groups. These results further affirm that sopite syndrome degrades task performance on top of frequency and acceleration.

Until now, little was known about the relationship between incidence of sopite syndrome and wind-induced building motion or about the effects of sopite syndrome on task performance. This research posits three possible explanations for the effect. One of the theories of motion sickness, the Postural Instability Theory, posits that “prolonged postural instability is the cause of motion sickness” (Riccio and Stoffregen, 1991, p. 231). Postural instability here does not necessarily mean frank loss of balance. Rather, postural instability is a deterioration of postural control, that is, an increase in magnitude and/or chaotic level of body sway that can persist over a long period of time. Recent research shows that postural instability precedes reports of motion sickness (for example, Stoffregen et al., 2013; Stoffregen et al., 2010; Stoffregen and Smart, 1998). Postural instability can appear within a time frame similar to sopite syndrome, that is, before the appearance of the overt symptoms of motion sickness. The first possible explanation for the degraded task performance observed in this chapter is that those participants suffering sopite syndrome, or mild motion sickness, may experience a greater degree of postural instability and this postural instability degrades their task performance. This postural instability, in turn, may induce either vibration breakthrough, visual blurring, an additional challenge to balance, or a combination of them. While the effects of vibration breakthrough and visual blurring are relatively explicit, the effects of challenges to balance are more complicated.

Although maintaining balance is mostly an automatic process, studies have shown that responding to challenges to balance requires some conscious attention, which causes a reduction in cognitive performance (for example Andersson et al., 2002; Chong et al., 2010; May et al., 2009; Mersmann et al., 2013). In this chapter, postural instability caused by sopite syndrome may have diverted participants' attention, resulting in a withdrawal, or lowering of attentional resources from cognitive processes such as hand-eye coordination on which the CTT performance is highly dependent. Withdrawing attentional resources from cognitive processes will result in degraded manual task performance. Kennedy et al. (2010), citing a study conducted by the National Aeronautics and Space Administration (NASA), reported that disturbances in hand-eye coordination may occur as a sole manifestation of motion sickness or may be present with other symptoms.

Second, sopite syndrome may act as a stressor that affects manual task performance. It has been known that sopite syndrome may act as a stressor that can affect cognitive performance, such as attention and its allocation, memory systems, problem solving, and decision making (Bourne and Yaroush, 2003). Lamb et al. (2014) suggest that sopite syndrome can be a stressor on occupants in wind-excited building environments. Matsangas et al. (2014) found that mild motion sickness, or sopite syndrome, may act as a stressor that causes a degradation of multi-tasking cognitive performance. As a stressor, sopite syndrome may interrupt the allocation of attentional resources for performing multiple cognitive tasks. The effects of sopite syndrome on complex cognitive tasks such as arithmetic tasks and short-term memory have been shown to be larger than on less cognitively demanding tasks such as visual and auditory tasks. Matsangas et al. (2014) suggested that sopite syndrome may distract participants by withholding or denying the use of attentional resources and push participants to perform the cognitive task in over-loaded, or near over-loaded zones, with limited attentional resource capacity.

Attentional resources of an individual are limited. The capacities of attentional resources can vary between individuals. Cognitive and other processes of a manual task may demand various amounts of attentional resources. Using a CTT as an example, hand-eye coordination, maintaining balance, and other processes demand various amounts of attentional resource from a limited capacity of an individual. Distributions of attentional resources to hand-eye coordination, maintaining balance, and other processes may be further affected with or without the appearance of sopite syndrome, which manifests as a stressor. Figure 5.16 demonstrates how distributions of attentional resources in an individual performing a CTT may evolve under four different scenarios. It should be noted that these distributions are illustrative only and should be considered qualitatively rather than quantitatively. Each case is described as follows.

If the attentional capacity is large and/or total demand of attentional resources is small, some attentional resources may be idle. Under static conditions and without the appearance of sopite syndrome, demands on attentional resources for balance and sopite syndrome are negligible. The majority of attentional resources are likely to be allocated to hand-eye coordination and other processes that related to the CTT, as shown in Case 1 of Figure 5.16.

Challenges to balance appear if the CTT is performed under the motion conditions studied. As mentioned earlier, challenges to balance require some conscious attention, which can cause a reduction in cognitive performance (for example Andersson et al., 2002; Chong et al., 2010; May et al., 2009; Mersmann et al., 2013). Hence, challenges to balance induced by low-frequency, low-acceleration motion may demand additional attentional resources. The additional attentional resources may come from the idle attentional resources. Consumption of the idle attentional resources may push the individual to perform the manual task in a near over-loaded zone or even over-loaded zone. Case 2 of Figure 5.16 represents a distribution of attentional resources, assuming the manual task is performed in an overloaded zone.

In a case where the capacity is small and/or idle attentional resources are exhausted, the additional attentional resources for balancing may be redirected away from hand-eye coordination and/or other processes to balancing. Case 3 of Figure 5.16 presents a distribution such that idle attentional resources are exhausted and attentional resources are diverted from hand-eye coordination and other processes to maintaining balance. In such a case, hand-eye coordination and/or other processes that are needed for task performance are likely to be compromised.

Sopite syndrome may appear if the individual continues the CTT under low-frequency, low-acceleration motion conditions. The appearance of sopite syndrome is likely to further interrupt attentional resource distribution. Without idle attentional resources, sopite syndrome may withdraw attentional resources from hand-eye coordination, balancing, other processes, or a combination of them, as shown in Case 4 of Figure 5.16.

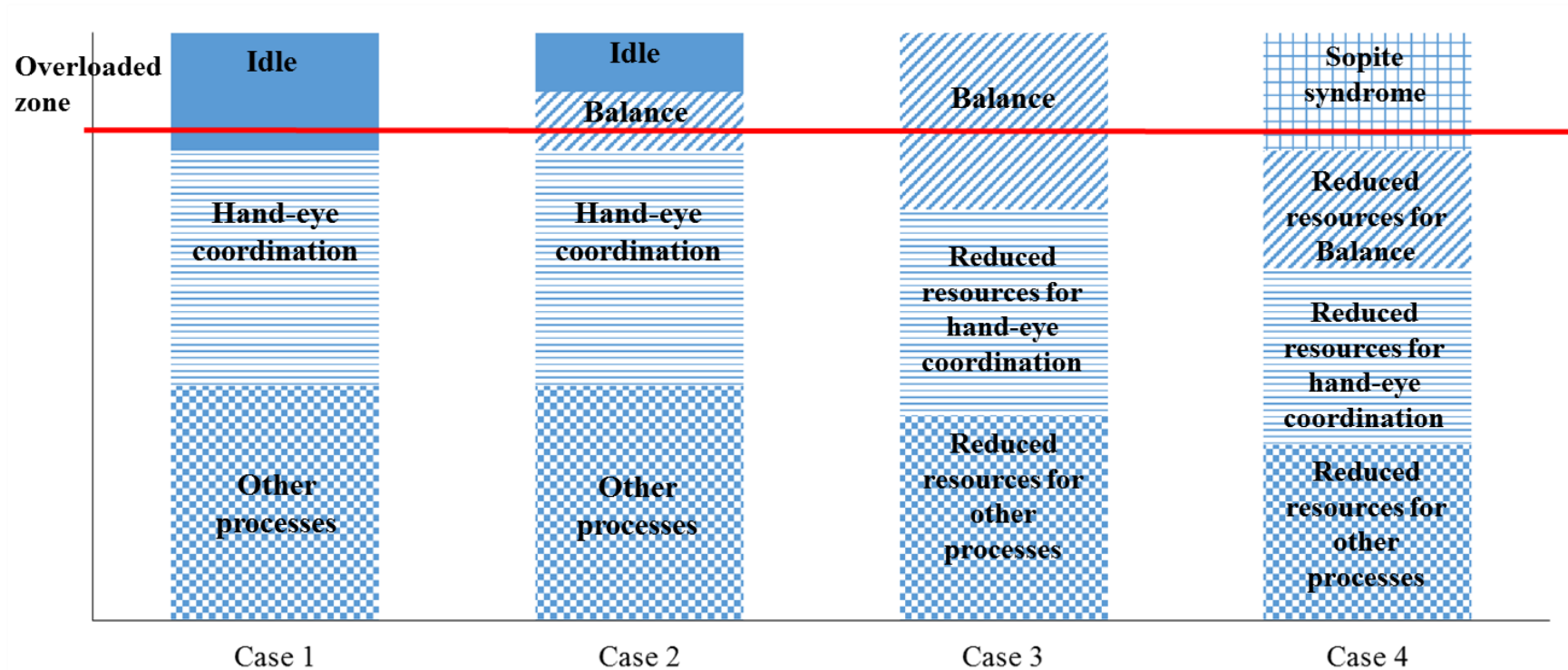


Figure 5.16. Attentional resource distributions of a participant performing the CTT under four operating cases. Case 1, under static condition with idle attentional resources and without appearance of sopite syndrome. Case 2, under motion conditions and performing CTT in an overloaded zone, idle attentional resources supply for balancing. Case 3, idle attentional resources are exhausted, attentional resources are diverted from hand-eye coordination and other processes to maintaining balance. Case 4, appearance of sopite syndrome withdraws attentional resources from hand-eye coordination, balancing, other processes, or a combination of them.

Third, sopite syndrome may affect motivation of participants to perform a manual task. It has also been argued that changes in motivation may influence the cognitive performance of humans suffering motion sickness. On one hand, motion sickness may reduce motivation resulting in performance decrements (Hettinger et al. 1990). Alternatively, increased motivation may alleviate effects of motion sickness such that individuals can complete a task without deterioration (Clark and Graybiel, 1961; Graybiel et al., 1965; Guedry et al., 1964). In this experiment, the duration was fixed and the reimbursement to participants was the same regardless of task performance. Therefore, there was no obvious driver to increase participants' motivation. On the other hand, the appearance of sopite syndrome may have reduced participants' motivation and resulted in performance degradation.

Changes in motivation can also be linked to a willingness to perform a task, that is, an individual's personality. Webb et al. (1981) found that under motion conditions internal subjects who perceived effort as an instrument of personal achievement performed better than external subjects who believed success and failure were outside their own influence. Individual factors are therefore likely to change a participant's motivation and further intervene in attentional resource distribution.

5.5.3 Effects of gender and motion direction on sopite syndrome severity

The results of this chapter show that gender and motion direction on sopite syndrome severity are not significant. These results are consistent with the findings presented in Chapter 4, which show that the effects of gender and motion direction were not significant for task performance. Some studies on low-frequency, low-acceleration motion found the effects of gender and motion direction on perception thresholds were minor (for example Kanda et al., 1988; Kojima et al., 1972; Tamura et al., 2006). This chapter consistently showed they were not significant on the severity of sopite syndrome.

5.6 Limitations

It is well-known that incidence of motion sickness is related to the duration of exposure, frequency and/or acceleration of the provocative motion (for examples, Golding and Kerguelen, 1992; Lawther and Griffin, 1988; McCauley et al., 1976; Money, 1970; O'Hanlon and McCauley, 1973). It is hypothesised that incidence and/or severity of sopite syndrome may also be related to exposure duration, frequency and/or acceleration of motion that occur in wind-excited buildings. However, this chapter focused on the effects of motion on manual task performance and was not designed to correlate incidence and/or severity of sopite syndrome with these factors. Since sopite syndrome may occur as a sole manifestation of motion sickness in wind-excited buildings (Lamb et al., 2013, 2014; Walton et al., 2011), future studies can be designed to relate incidence and/or severity of sopite syndrome with exposure duration, frequency and/or acceleration of motion.

Results of this chapter may underestimate the effects of sopite syndrome on manual task performance in wind-excited buildings as participants only performed a manual task under controlled laboratory environments. The laboratory environments provided minimal distractions from other sources, thus reducing demand on attentional resources. However, in a real building, occupants are like to be concurrently performing multiple tasks that demand large amounts of attentional resources. These tasks may act like additional distractions that push the occupants to perform in near-overloaded or overloaded zones. As discussed earlier, sopite syndrome may act as a stressor that reduces the attentional resources available for a manual task. In such situations, occupants who are sensitive to the appearance of sopite syndrome consciously re-distribute attentional resources which can further degrade manual task performance.

5.7 Conclusions

Degradation effects of low-frequency, low-acceleration motion on manual task performance have been demonstrated in Chapter 4. This chapter investigated the incidence of sopite syndrome under low-frequency, low-acceleration motion conditions and the effects of sopite syndrome on manual task performance. The results show that the combined influence of approximately 30 minutes exposure to motion across all conditions is sufficient to cause some form of motion sickness in most participants. Symptoms of sopite syndrome such as feeling drowsy, tired, fatigue, uneasy, annoyed, and/or irritated are the most frequently reported symptoms of motion sickness. These results affirm that motion sickness occurring in wind-excited buildings mostly manifest as symptoms of sopite syndrome (Lamb et al., 2014; Walton et al., 2011).

This is the first study correlating sopite syndrome severity with manual task performance under low-frequency, low-acceleration motion that is comparable to wind-induced building motion. The results show an inverse relationship between sopite syndrome severity and manual task performance; participants who reported symptoms of sopite syndrome, or mild motion sickness, performed significantly worse than participants who were relatively unaffected.

Postural Instability Theory posits that “prolonged postural instability is the cause of motion sickness” (Riccio and Stoffregen, 1991, p.231). According to this theory, participants suffering sopite syndrome, or mild motion sickness, are likely to exhibit a greater degree of postural instability. This postural instability may either induce vibration breakthrough, visual blurring, an additional challenge to balance, or a combination of them. While the effects of vibration breakthrough and visual blurring are relatively explicit, effects of challenge to balance is more complicated. The challenge to balance caused by sopite syndrome induced postural instability may divert attentional resources from cognitive processes such as hand-eye coordination to maintaining balancing. The activation levels of leg muscles involved in maintaining balance sheds some light on the postural stability of participants who suffered sopite syndrome. This aspect of the study is presented in Chapter 6.

Sopite syndrome may also act as a stressor. It can further intervene in the distribution of attentional resources for performing a manual task. In real wind-excited buildings, the effects of sopite syndrome on manual task performance could become more complicated. The effects may depend on the frequency, acceleration, and duration of wind-induced building motion, the severity of sopite syndrome, individual characteristics, motivation, and demand on attentional resources for other tasks concurrently being carried out with the manual task. Further studies are needed to investigate these relationships.

CHAPTER 6

EFFECTS OF LOW-FREQUENCY, LOW-ACCELERATION FORE-AFT MOTION ON A CONTINUOUS TRACKING TASK – A HUMAN PHYSIOLOGICAL PERSPECTIVE

6.1 Introduction

This chapter builds on previous chapters and investigates the relationships between the activation levels of leg muscles involved in maintaining balance and influencing factors including performing a manual task, frequency, acceleration, and sopite syndrome severity. Chapter 4 reported the effects of low-frequency, low-acceleration motion on performance in a continuous tracking task (CTT). The results showed that CTT performance decreased with an increase in acceleration from 8 milli-g to 30 milli-g. The effects of acceleration relate to the increase in inertial force acting on the human body, which in turn, increases body sway. The effects of frequency on CTT performance are complex. CTT performance varies nonlinearly across frequency. CTT performance is degraded as frequency increases from 0.125 Hz to 0.5 Hz. However, the degradation is alleviated as the frequency increases from 0.5 Hz to 1 Hz. It is believed that the nonlinear characteristic is associated with the resonant characteristics of the human body, which accordingly, affect body sway across frequency.

Chapter 5 showed that exposure to low-frequency, low-acceleration motion provokes symptoms of sopite syndrome. It also showed that participants suffering more severe symptoms of sopite syndrome performed worse in the CTT than those suffering less severe symptoms. One possible explanation for the effects of sopite syndrome on the CTT performance degradation is that participants suffering sopite syndrome may exhibit a greater degree of postural instability, and this postural instability degrades task performance. Motion environments may degrade manual task performance through biomechanical influences and/or by creating balance problems (Wertheim, 1998). Burton et al. (2011) suggested that the young and fit participants in their study were able to effectively compensate for the difficulty in maintaining balance caused by bi-direction, narrow-band random motion so that the motion did not degrade manual task performance. However, Burton et al. (2011) did not provide any evidence to support this suggestion.

It is proposed that the degradation of CTT performance is likely to be associated with body sway because of the effects of acceleration, frequency, and sopite syndrome. If so, the variation patterns of the activation levels of the leg muscles involved in maintaining balance across acceleration, frequency, and sopite syndrome are likely to be similar to the patterns between CTT performance and acceleration, frequency, and sopite syndrome severity. Similarly, carrying out the compensatory action for maintaining balance and/or performing the CTT will alter the activation levels of the leg muscles. The relationships between these factors provide evidence to support the findings reported in Chapters 4 and 5 and demonstrate whether compensatory action was carried out by the participants.

Most studies on human balance discuss postural control in the fore-aft direction (Winter, 1995). As body motion in the fore-aft direction is the most important for maintaining balance recovery (Hwang et al., 2009), this chapter focuses on the effects of low-frequency, low-acceleration motion on activation levels of leg muscles involved in maintaining postural control in the fore-aft direction only. The activation levels required for maintaining balance were measured primarily from soleus (SOL) and tibialis anterior (TA), the leg muscles involved in maintaining balance in the fore-aft direction. In particular, this chapter focuses on:

- i) the effects of performing a manual task on the activation levels of SOL and TA,
- ii) the variations of the activation levels of SOL and TA across acceleration and frequency, and
- iii) the effects of sopite syndrome severity on the activation levels of SOL and TA.

6.2 Methodology

Results presented in this chapter were derived from the data collected from the motion simulator experiment, as detailed in Chapter 3. The motion simulator experiment primarily used a continuous tracking task (CTT) as a paradigm to investigate the effects of low-frequency, low-acceleration motion on manual task performance. Three acceleration magnitudes (8, 16, and 30 milli-g) and four frequencies (0.125, 0.25, 0.5, and 1 Hz) were used to produce 12 motion conditions for both fore-aft and lateral directions. Twenty participants completed the experiment under fore-aft motion conditions and another 20 completed the experiment under lateral motion conditions. As this chapter focuses on the activation levels of leg muscles involved in maintaining balance in the fore-aft direction only, the leg muscle activation levels were measured from the 20 participants who completed the experiment under fore-aft motion conditions. The leg muscle activation levels were measured using electromyography, a measurement technique used to record the electrical signals emanating from muscles. The computer-based data acquisition and analysis system described in Chapter 3 was used for the measurement. The severity of sopite syndrome in the 20 participants was measured using the Motion Sickness Assessment Questionnaire (Gianaros et al., 2001). Other details of the motion simulator experiment have been presented in Chapter 3.

6.3 Analysis

6.3.1 Quantifying activation levels of leg muscles

The standard deviation of an electromyographic signal (EMG_{SD}) was determined to quantify the activation levels of SOL and TA. It measured the power of the EMG signal, which represented the activation levels or energy requirements of the muscles (De Luca, 2002). EMG_{SD} was calculated from 64-second long leg muscle EMG signals to determine the activation levels of SOL and TA measured under all motion conditions. The variation patterns of EMG_{SD} of the SOL and TA across acceleration and frequency were determined.

6.3.2 Normalised standard deviation electromyographic signal

EMG_{SD} was normalised to focus on the effects of motion conditions but eliminate other effects, such as individual differences caused by muscle size, location of surface electrodes, individual response characteristics to motion, and performing the CTT. When the participants were not performing the CTT, the EMG_{SD} without performing CTT was normalised according to Equation 6.1. The normalised EMG_{SD} without performing CTT was defined as the EMG_{SD} measured under a motion condition, divided by the EMG_{SD} measured under the embedded static condition and both were measured without performing the CTT.

Equation 6.1

Normalised EMG_{SD} without performing CTT

$$= \left[\frac{EMG_{SD} \text{ measured under a motion condition}}{EMG_{SD} \text{ measured under the embedded static condition}} \right]_{\text{without performing CTT}}$$

When the participants were performing the CTT, the normalised EMG_{SD} performing CTT was defined similarly, as shown in Equation 6.2. The EMG_{SD} without performing CTT and EMG_{SD} performing CTT were used in mixed-design ANOVAs to investigate the relationship between participants' sopite-related motion sickness score and the activation levels of leg muscles, with and without performing the CTT. Section 6.3.3 details the mixed-design ANOVAs.

Equation 6.2

Normalised EMG_{SD} performing CTT

$$= \left[\frac{EMG_{SD} \text{ measured under a motion condition}}{EMG_{SD} \text{ measured under the embedded static condition}} \right]_{\text{performing CTT}}$$

6.3.3 Statistical analysis

6.3.3.1 Effects of performing the CTT, acceleration, and frequency on the activation levels of leg muscles

Three-way repeated-measures ANOVAs were used to investigate the effects of performing the CTT, frequency, and acceleration on the activation levels of leg muscles. The three within-subjects factors of the three-way repeated-measures ANOVAs were performing the CTT, frequency, and acceleration. The dependent variables of the three-way repeated-measures ANOVAs were the EMG_{SD} of either the SOL or TA.

6.3.3.2 Effects of symptoms of sopite syndrome on activation levels of leg muscles

Mixed-design three-way ANOVAs were used to investigate how sopite syndrome affected the activation levels of participants' leg muscles, with and without performing the CTT. Frequency and acceleration were the within-subjects factors and the severity of sopite syndrome was the between-subjects factor. The severity of participants' sopite syndrome was determined based on the Motion Sickness Assessment Questionnaire (MSAQ) sopite-related subscale score. Details of the sopite syndrome severity analysis can be found in Chapter 5. The EMG_{SD} without performing CTT and EMG_{SD} performing CTT of either SOL or TA were the dependent variables of the mixed-design three-way ANOVAs.

6.4 Results

In this section, the standard deviations of the electromyographic signal (EMG_{SD}) of the soleus (SOL) and tibialis anterior (TA) are presented to indicate the activation levels of the leg muscles required for maintaining balance. Repeated measures ANOVAs demonstrate the effects of performing the CTT, frequency, and acceleration on EMG_{SD} . The participants were separated into two groups based on their Motion Sickness Assessment Questionnaire (MSAQ) sopite-related subscale score; group one had high sopite-related scores and group two had low sopite-related scores. The results of statistical analyses determining whether the severity of sopite syndrome had any effect on normalised activation levels of the leg muscles and CTT performance are then presented.

6.4.1 Soleus EMG

A three-way repeated-measures ANOVA shows the main effects of performing the CTT, frequency, and acceleration on the standard deviation electromyographic (EMG_{SD}) of the soleus (SOL) are significant. Interaction effects between performing the CTT and frequency, and between frequency and acceleration on the SOL EMG_{SD} are also significant. Statistical results of the three-way repeated-measures ANOVA are summarised in Table 6.1. .

Table 6.1. A summary of a three-way repeated-measures ANOVA on SOL EMG_{SD}.

Effect	<i>F</i>	<i>p-value</i>
Main effect of performing CTT	<i>F</i> (1, 19) = 4.838	0.040
Main effect of frequency	<i>F</i> (3, 57) = 9.386	<0.001
Main effect of acceleration	<i>F</i> (2, 38) = 39.029	<0.001
Interaction effect between performing CTT and frequency	<i>F</i> (3, 57) = 3.278	0.027
Interaction effect between performing CTT and acceleration	<i>F</i> (2, 38) = 2.345	0.110
Interaction effect between frequency and acceleration	<i>F</i> (6, 114) = 5.553	<0.001
Interaction effect between performing CTT, frequency, and acceleration	<i>F</i> (6, 114) = 1.038	0.405

6.4.1.1 Main effect of performing CTT

Performing the CTT significantly increased the SOL EMG_{SD}, as shown in Figure 6.1. Mean and standard deviation values of the SOL EMG_{SD}, with and without performing the CTT, are summarised in Table 6.2. The result indicates that participants increased the activation levels of the SOL for performing the CTT. This increase in the SOL EMG_{SD}, due to performing the CTT, equates to an effect size of 0.15 (Cohen's *d*). The effect size of 0.15 suggests that performing the CTT increased the SOL EMG_{SD} by approximately 0.15 standard deviation.

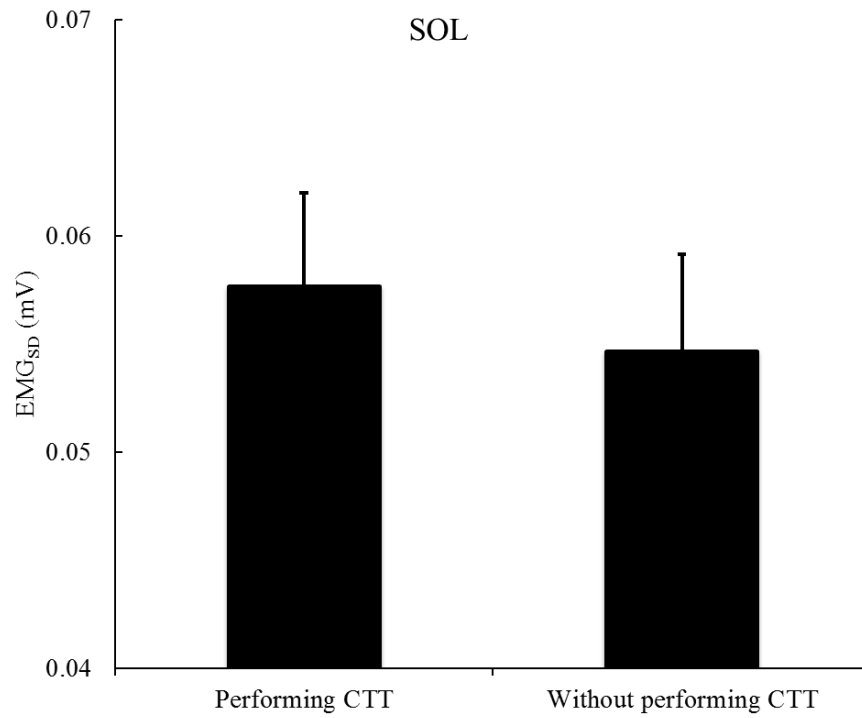


Figure 6.1. SOL EMG_{SD} (mean \pm S.E.) of participants ($N = 20$), with and without performing CTT. Performing CTT significantly increases SOL EMG_{SD}.

Table 6.2. Mean and standard deviation of SOL EMG_{SD}, with and without performing CTT.

	Mean (mV)	Standard deviation (mV)
Performing CTT	0.058	0.0193
Without performing CTT	0.055	0.0202

6.4.1.2 Main effect of acceleration

SOL EMG_{SD} increased with increase in acceleration, as shown in Figure 6.2. Mean and standard deviation values of the SOL EMG_{SD} across acceleration are summarised in Table 6.3. Pairwise comparisons show that SOL EMG_{SD} measured at 30 milli-g motion conditions are significantly higher than those measured at 8 milli-g ($p\text{-value} < 0.001$) and 16 milli-g ($p\text{-value} < 0.001$) motion conditions. Similarly, the SOL EMG_{SD} measured at 16 milli-g motion conditions are significantly higher than those measured at 8 milli-g ($p\text{-value} = 0.004$). These results indicate that the activation level of the SOL increases as acceleration increases monotonically from 8 milli-g to 30 milli-g. The increase of the SOL EMG_{SD} due to acceleration equates to an effect size of 0.85 (Cohen's d), compared with the SOL EMG_{SD} measured at 8 milli-g against 30 milli-g motion conditions. The SOL EMG_{SD} measured at 30 milli-g is approximately 0.85 standard deviation greater than that measured at 8 milli-g.

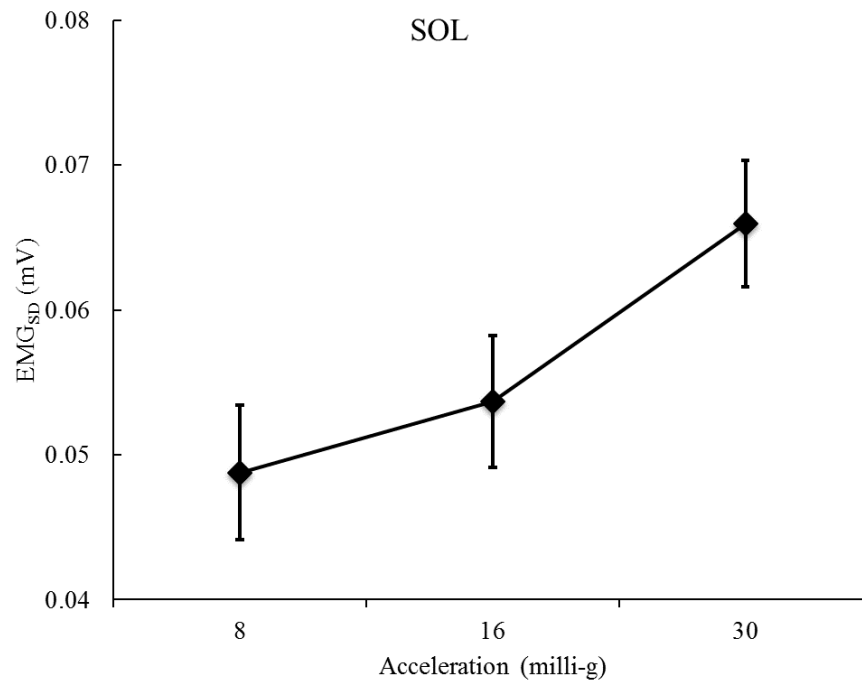


Figure 6.2. SOL EMG_{SD} (mean \pm S.E.) of participants ($N = 20$) across acceleration. SOL EMG_{SD} increases as acceleration increases from 8 milli-g to 30 milli-g.

Table 6.3. Mean and standard deviation of SOL EMG_{SD} across acceleration.

Acceleration (milli-g)	Mean (mV)	Standard deviation (mV)
8	0.049	0.0207
16	0.054	0.0204
30	0.066	0.0195

6.4.1.3 Main effect of frequency

The SOL EMG_{SD} shows a highly nonlinear characteristic with frequency. It increases as frequency increases from 0.125 Hz to 0.5 Hz, then drops at 1 Hz, as shown in Figure 6.3. The variation pattern is similar to that determined between CTT performance and frequency presented in Chapter 4. The mean and standard deviation values of SOL EMG_{SD} determined at each frequency are summarised in Table 6.4. Pairwise comparisons further affirm that SOL EMG_{SD} measured at 0.5 Hz are significantly higher than the other test frequencies, particularly 0.125 Hz ($p\text{-value} = 0.004$) and 1 Hz ($p\text{-value} = 0.001$) motion conditions. The largest difference in the SOL EMG_{SD} due to frequency exists between 0.5 Hz and 0.125 Hz motion conditions, equating to an effect size of 0.31 (Cohen's d). The effect size of 0.31 represents the SOL EMG_{SD}, measured at 0.5 Hz, is approximately 0.31 standard deviation greater than that at 0.125 Hz.

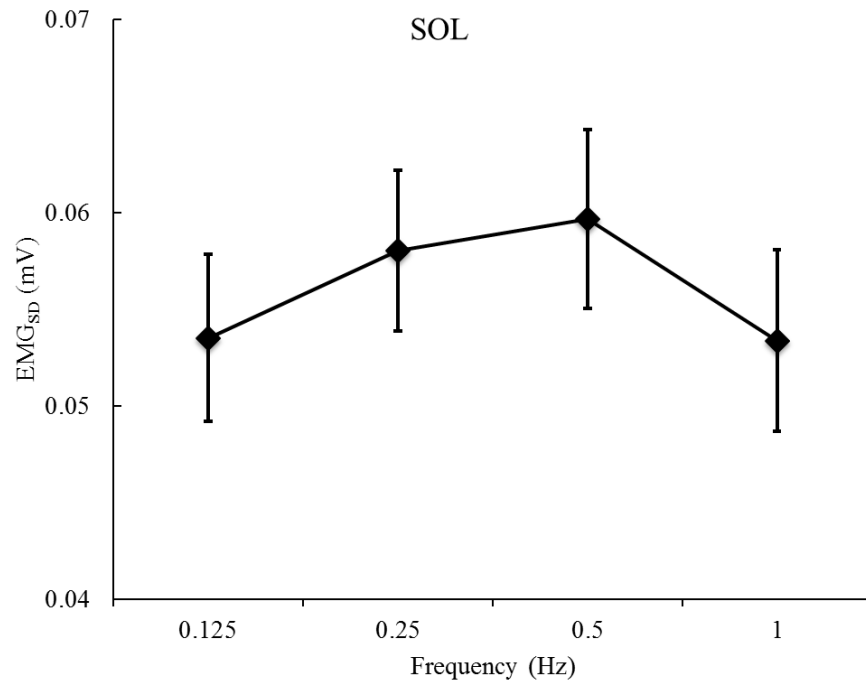


Figure 6.3. SOL EMG_{SD} (mean \pm S.E.) of participants ($N = 20$) across frequency. SOL EMG_{SD} shows a nonlinear relationship with frequency.

Table 6.4. Mean and standard deviation of SOL EMG_{SD} across frequency.

Frequency (Hz)	Mean (mV)	Standard deviation (mV)
0.125	0.054	0.0193
0.25	0.058	0.0186
0.5	0.060	0.0207
1	0.053	0.0210

6.4.1.4 Interaction effect between frequency and performing the CTT

The interaction effect between performing the CTT and frequency significantly affected SOL EMG_{SD}. The SOL EMG_{SD}, performing the CTT, was generally greater than the SOL EMG_{SD}, without performing the CTT, as shown in Figure 6.4. Regardless of whether the participants were performing the CTT or not, SOL EMG_{SD} was the highest at 0.5 Hz and closely followed by 0.25 Hz. The results suggest that the activation level of the SOL may be saturated in response to 0.25 and 0.5 Hz motion. The variation patterns of SOL EMG_{SD} across frequency, regardless of whether they were performing the CTT or not, are consistent with the variation pattern reported in Section 6.4.1.3 for the main effect of frequency. It is noteworthy that performing the CTT raised the SOL EMG_{SD} most noticeably at 0.125 Hz and 1 Hz, the two low frequency and high frequency ends of the tested frequency range. This highlights the interaction effect between performing the CTT and frequency. This is elaborated in the Discussion section.

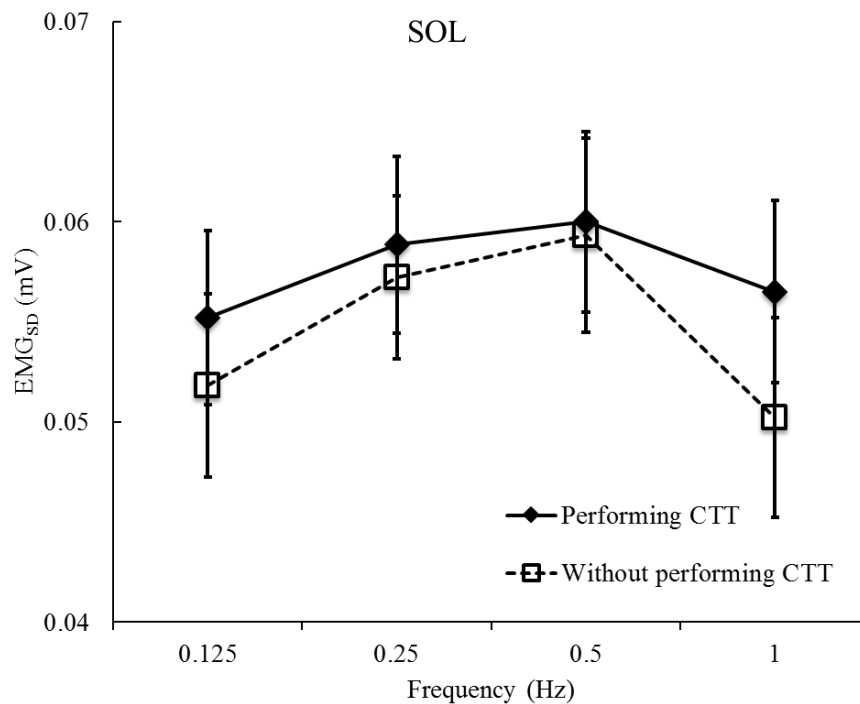


Figure 6.4. SOL EMG_{SD} (mean \pm S.E.), with and without performing CTT, of participants ($N = 20$) across frequency.

6.4.1.5 Interaction effect between acceleration and frequency

Interaction effect between acceleration and frequency on the SOL EMG_{SD} was significant. The nonlinear relationship between the SOL EMG_{SD} and frequency at 30 milli-g motion conditions was the most prominent among the accelerations, as shown in Figure 6.5. Evidently, 30 milli-g acceleration accentuates the nonlinear characteristic of frequency on the activation level of the SOL, which peaks at around 0.25 to 0.5 Hz.

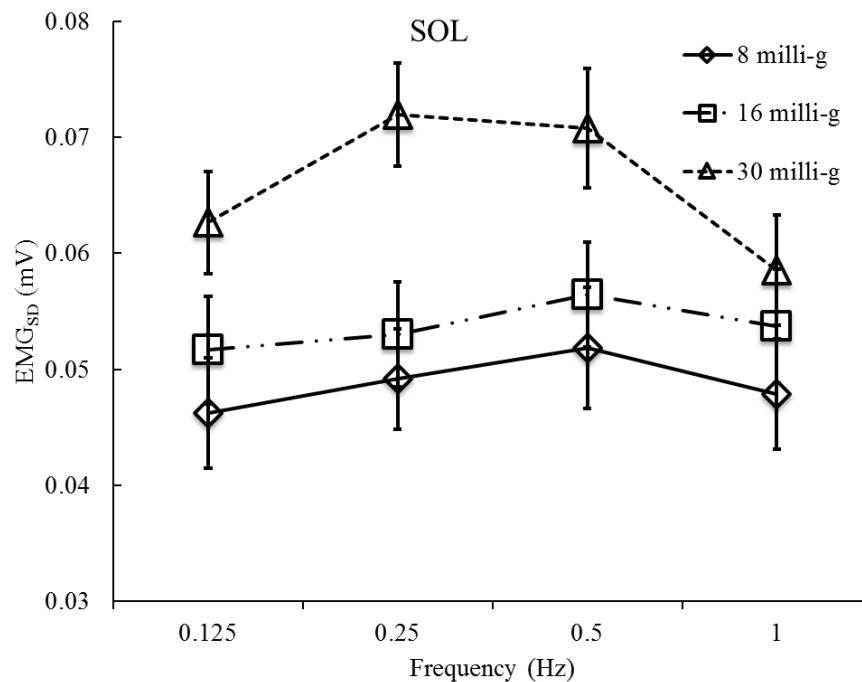


Figure 6.5. SOL EMG_{SD} (mean \pm S.E.) of participants ($N = 20$) across frequency and separated in accordance with acceleration. The nonlinear relationship between SOL EMG_{SD} and frequency at 30 milli-g is the most prominent.

6.4.2 Tibialis anterior EMG

A three-way repeated-measures ANOVA shows that the main effects of performing the CTT, frequency, and acceleration on EMG_{SD} of the tibialis anterior (TA) are significant. The interaction effects on the TA EMG_{SD} between performing the CTT and acceleration, and between frequency and acceleration are also significant. Statistical results of the three-way repeated-measures ANOVAs are summarised in Table 6.5.

Table 6.5. A result summary of a three-way repeated-measures ANOVA on TA EMG_{SD}.

Effect	<i>F</i>	<i>p-value</i>
Main effect of performing CTT	<i>F</i> (1, 19) = 14.514	0.001
Main effect of frequency	<i>F</i> (3, 57) = 37.411	<0.001
Main effect of acceleration	<i>F</i> (2, 38) = 53.241	<0.001
Interaction effect between performing CTT and frequency	<i>F</i> (3, 57) = 0.662	0.579
Interaction effect between performing CTT and acceleration	<i>F</i> (2, 38) = 7.982	0.001
Interaction effect between frequency and acceleration	<i>F</i> (6, 114) = 20.038	<0.001
Interaction effect between performing CTT, frequency and acceleration	<i>F</i> (6, 114) = 1.580	0.159

6.4.2.1 Main effect of performing CTT

Performing the CTT significantly reduced the EMG_{SD} of the TA, as shown in Figure 6.6. This is in contrast to the effect on the SOL EMG_{SD} reported in Section 6.4.1.1 . Seemingly, this is due to the difference between the physiological functions of the TA and the SOL in maintaining balance, which is detailed in the Discussion section. Mean and standard deviation values of TA EMG_{SD} measured when the participants were or were not performing the CTT are summarised in Table 6.6. The results indicate that performing the CTT reduced the activation level of the TA with an effect size of 0.39 (Cohen's *d*); performing the CTT decreased the TA EMG_{SD} by approximately 0.39 standard deviation.

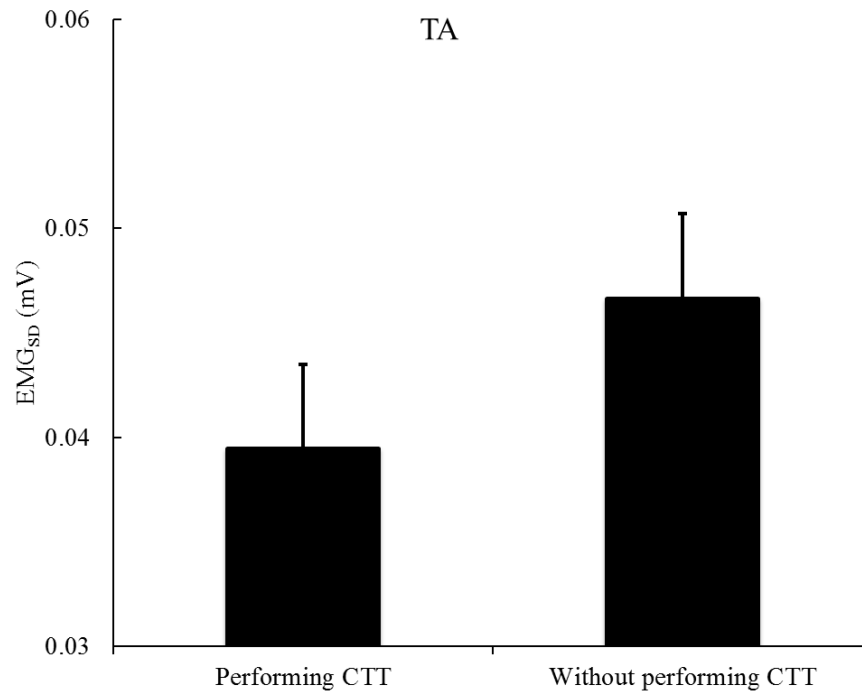


Figure 6.6. TA EMG_{SD} (mean \pm S.E.) measured when participants ($N = 20$) were or were not performing CTT.

Table 6.6. Mean and standard deviation of TA EMG_{SD} when participants were or were not performing CTT.

	Mean (mV)	Standard deviation (mV)
Performing CTT	0.039	0.0179
Without performing CTT	0.047	0.0184

6.4.2.2 Main effect of acceleration

The TA EMG_{SD} increased with increases in acceleration, as shown in Figure 6.7. The mean and standard deviation values of the TA EMG_{SD} across acceleration are summarised in Table 6.7. The results indicate that the activation level of the TA increases as acceleration increases from 8 milli-g to 30 milli-g. Pairwise comparisons show that the TA EMG_{SD} measured at 8, 16, and 30 milli-g motion conditions were significantly different from each other ($p\text{-value} < 0.001$). The increase due to acceleration equates to an effect size of 2.22 (Cohen's d) when comparing the TA EMG_{SD} measured at 8 milli-g against 30 milli-g motion conditions. The TA EMG_{SD} measured at 30 milli-g is approximately 2.22 standard deviation greater than that measured at 8 milli-g.

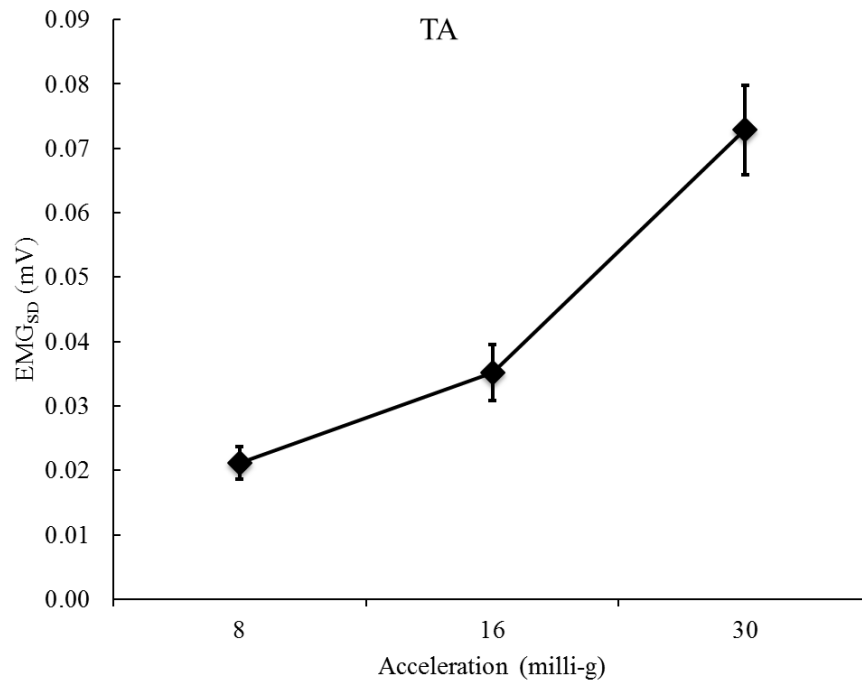


Figure 6.7. TA EMG_{SD} (mean \pm S.E.) of participants ($N = 20$) across acceleration. TA EMG_{SD} increases as acceleration increases from 8 milli-g to 30 milli-g.

Table 6.7. Mean and standard deviation of TA EMG_{SD} across acceleration.

Acceleration (milli-g)	Mean (mV)	Standard deviation (mV)
8	0.021	0.0114
16	0.035	0.0195
30	0.073	0.0310

6.4.2.3 Main effect of frequency

TA EMG_{SD} shows a nonlinear characteristic with frequency, with increases from 0.125 Hz to 0.25 Hz and 0.5 Hz, then drops at 1 Hz, as shown in Figure 6.8. The variation pattern of TA EMG_{SD} across frequency, an inverted U-shape, is similar to that determined between CTT performance and frequency presented in Chapter 4. Mean and standard deviation values of the TA EMG_{SD} determined at each frequency are summarised in Table 6.8. The largest differences in the TA EMG_{SD} were measured between 0.25 Hz and 1 Hz motion conditions. The difference equates to an effect size of 1.51 (Cohen's d). The TA EMG_{SD} measured at 0.25 Hz is approximately 1.51 standard deviation greater than that measured at 1 Hz.

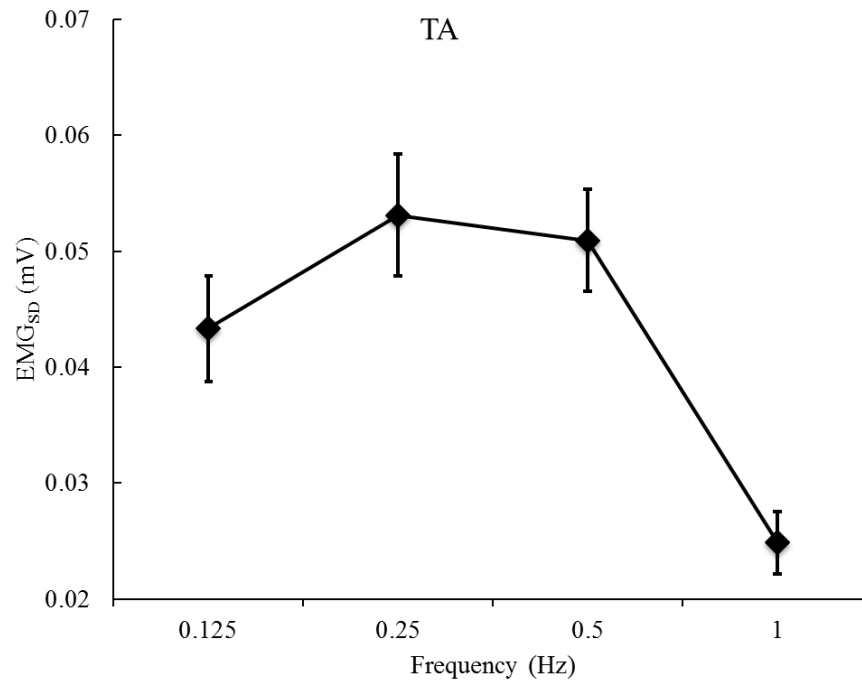


Figure 6.8. TA EMG_{SD} (mean \pm S.E.) of participants ($N = 20$) across frequency. TA EMG_{SD} shows a nonlinear relationship with frequency.

Table 6.8. Mean and standard deviation of TA EMG_{SD} across frequency.

Frequency (Hz)	Mean (mV)	Standard deviation (mV)
0.125	0.043	0.0205
0.25	0.053	0.0236
0.5	0.051	0.0197
1	0.025	0.0120

6.4.2.4 Interaction effect between acceleration and performing the CTT

The interaction effect between performing the CTT and acceleration significantly affects TA EMG_{SD}. The TA EMG_{SD} increases as acceleration increases from 8 to 30 milli-g, regardless of whether the participants were, or were not, performing the CTT, as shown in Figure 6.9. The TA EMG_{SD} measured when the participants were not performing the CTT was generally greater than when the participants were performing the CTT. However, performing the CTT reduced the increasing rate of TA EMG_{SD} as acceleration increased from 8 milli-g to 30 milli-g. Since the TA is generally activated to adjust backward body sway when balancing is jeopardised, the activation level of the TA actually reflects the stability level of the human body. This provides evidence that compensatory actions are carried out for maintaining balance and/or performing the CTT. This is further elaborated in the Discussion section.

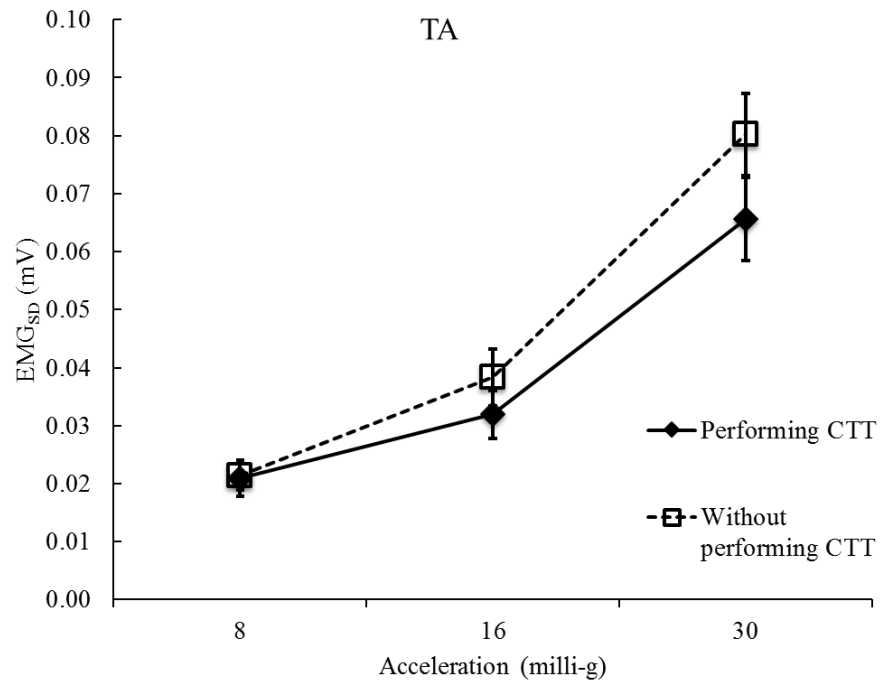


Figure 6.9. TA EMG_{SD} (mean \pm S.E.) of participants ($N = 20$) across acceleration and separated according to whether participants were or were not performing the CTT.

6.4.2.5 Interaction effect between acceleration and frequency

The interaction effect between acceleration and frequency significantly affects TA EMG_{SD}. The nonlinear relationship between TA EMG_{SD} and frequency at 30 milli-g motion conditions is the most prominent among the accelerations, as shown in Figure 6.10. This result indicates that 30 milli-g (high acceleration) motion conditions amplify the nonlinear effects of frequency on the activation level of the TA, which peaks at around 0.25 Hz and 0.5 Hz.

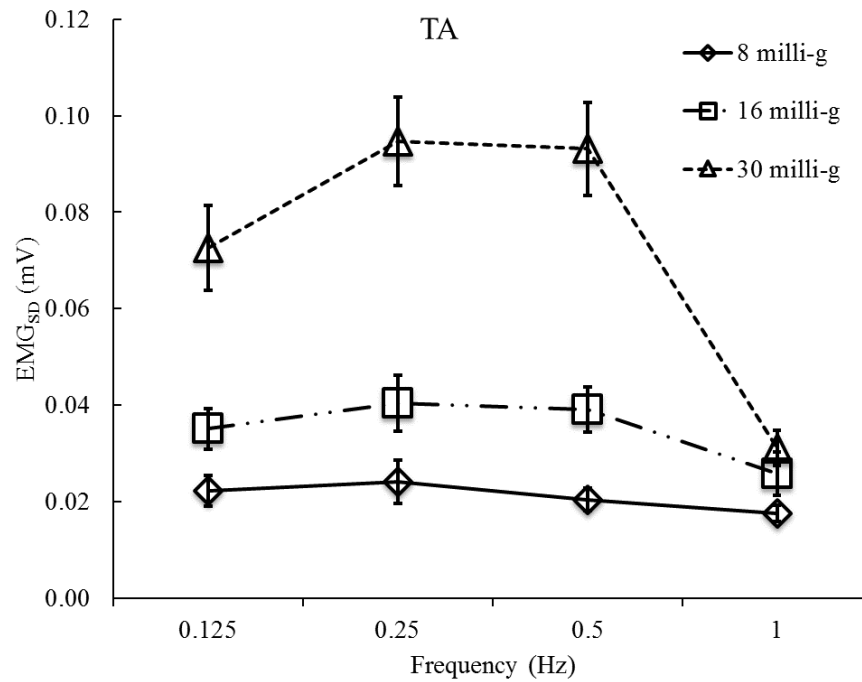


Figure 6.10. TA EMG_{SD} (mean \pm S.E.) of participants ($N = 20$) across frequency and separated according to acceleration. The nonlinear relationship between TA EMG_{SD} and frequency at 30 milli-g is the most prominent.

6.4.3 Motion sickness subscale scores and grouping of participants based on sopite-related subscale score

In Chapter 5, the effects of exposure to low-frequency, low-acceleration motion on motion sickness subscale scores were determined for the 40 participants who completed the CTT experiment: 20 participants under fore-aft motion conditions and the others under lateral motion conditions. The results showed the effects of exposure to the low-frequency, low-acceleration motion on the sopite-related subscale score of the 40 participants were significant. The sopite-related subscale scores of the 40 participants were increased due to exposure to the low-frequency, low-acceleration motion.

As this chapter focuses on the activation levels of the leg muscles involved in maintaining balance in the fore-aft direction only, the leg muscle activation levels were measured from the 20 participants who completed the experiment under fore-aft motion conditions. Similarly, the effects of exposure to low-frequency, low-acceleration motion on sopite-related subscale scores were determined for the 20 participants who completed the experiment under the fore-aft motion conditions. This forms a subset of the results presented in Chapter 5. To avoid repeated presentation, the results of the 20 participants are presented in Appendix D for reference. In summary, the results of the 20 participants show that the increases in sopite-related subscale score due to the exposure to low-frequency, low-acceleration fore-aft motion are significant. The results are consistent with those presented in Chapter 5.

In order to investigate the effects of sopite syndrome on the activation levels of leg muscles and CTT task performance, the 20 participants who completed the experiment under fore-aft motion conditions were divided into high and low sopite syndrome severity groups based on their sopite relate subscale scores. Among the 20 participants, 9 participants were assigned to the high sopite syndrome severity group and 11 participants were assigned to the low sopite syndrome severity group, as presented in Appendix E.

6.4.4 Effects of sopite syndrome on normalised standard deviation EMG signals of leg muscles

This section presents the results of statistical analyses investigating the effects of sopite syndrome on normalised standard deviation EMG signals (EMG_{SD}) of the leg muscles of the 20 participants, with or without performing the CTT. The normalised EMG_{SD} without performing CTT and normalised EMG_{SD} performing CTT, were determined using Equation 6.1 and Equation 6.2 respectively, as presented in Section 6.3.2 . The normalised EMG_{SD} focus on the effects of motion conditions but eliminate other effects, such as individual differences caused by muscle size, location of surface electrodes, individual response characteristics to motion, and performing the CTT.

6.4.4.1 Without performing CTT

Results of a mixed-design three-way ANOVA, with frequency and acceleration as the within-subjects factors and sopite syndrome severity groups as the between-subjects factor, show that the main and interaction effects of sopite syndrome severity are not significant on normalised EMG_{SD} of the SOL and TA when participants were not performing the CTT. The results of the mixed-design three-way ANOVAs for the SOL and TA are summarised in Table 6.9 and Table 6.10 respectively. Without performing the CTT, the normalised activation levels of the SOL and TA of the high and low sopite syndrome severity group participants are similar.

Table 6.9. A summary of main and interaction effects of sopite syndrome level on SOL EMG_{SD} of a mixed-design three-way ANOVA. Normalised SOL EMG_{SD} were measured when participants ($N = 20$) were not performing CTT.

Effects	<i>F</i>	<i>p-value</i>
Main effect of sopite syndrome severity	$F(1, 18) = 0.246$	0.626
Interaction effect between sopite syndrome severity and frequency	$F(3, 54) = 0.668$	0.575
Interaction effect between sopite syndrome severity and acceleration	$F(2, 36) = 0.017$	0.983
Interaction effect between sopite syndrome severity, frequency, and acceleration	$F(6, 108) = 0.307$	0.932

Table 6.10. A summary of main and interaction effects of sopite syndrome level on normalised TA EMG_{SD} of a mixed-design three-way ANOVA. Normalised TA EMG_{SD} were measured when participants ($N = 20$) were not performing CTT.

Effects	<i>F</i>	<i>p-value</i>
Main effect of sopite syndrome severity	$F(1, 18) = 0.448$	0.512
Interaction effect between sopite syndrome severity and frequency	$F(3, 54) = 0.406$	0.749
Interaction effect between sopite syndrome severity and acceleration	$F(2, 36) = 0.258$	0.774
Interaction effect between sopite syndrome severity, frequency, and acceleration	$F(6, 108) = 0.421$	0.864

6.4.4.2 Performing CTT

In contrast, when the participants were performing the CTT, the main effect of the sopite syndrome severity on the normalised SOL EMG_{SD} was significant (p -value = 0.015) while that on the normalised TA EMG_{SD} was close to reach significance (p -value = 0.074). Results of the mixed-design three-way ANOVA with frequency and acceleration as the within-subjects factors and sopite syndrome severity as the between-subjects factor on normalised EMG_{SD} of the SOL and TA are summarised in Table 6.11.

Table 6.11. A summary of main and interaction effects of sopite syndrome severity on normalised EMG_{SD} of SOL and TA of mixed-design three-way ANOVAs. Normalised EMG_{SD} of SOL and TA were measured when participants ($N = 20$) were performing CTT.

Leg muscle	Effects	F	p -value
SOL	Main effect of sopite syndrome severity	$F(1, 18) = 7.178$	0.015
	Interaction effect between sopite syndrome severity and frequency	$F(3, 54) = 2.469$	0.072
	Interaction effect between sopite syndrome severity and acceleration	$F(2, 36) = 3.456$	0.042
	Interaction effect between sopite syndrome severity, frequency, and acceleration	$F(6, 108) = 0.836$	0.545
TA	Main effect of sopite syndrome severity	$F(1, 18) = 3.587$	0.074
	Interaction effect between sopite syndrome severity and frequency	$F(3, 54) = 1.474$	0.232
	Interaction effect between sopite syndrome severity and acceleration	$F(2, 36) = 3.575$	0.038
	Interaction effect between sopite syndrome severity, frequency, and acceleration	$F(6, 108) = 0.473$	0.827

When the participants were performing the CTT, the normalised EMG_{SD} of both the SOL and TA of the high sopite syndrome severity participants is greater than that of the low sopite syndrome severity group, as shown in Figure 6.11 and Figure 6.12 respectively. The results of Section 6.4.4.1 show that, without performing the CTT, the difference in the normalised activation levels of the leg muscles between the high and low sopite syndrome severity group participants were not significant. The results presented in this section, performing the CTT, are in contrast to the normalised activation levels of the leg muscles when the participants were not performing the CTT. This may be because the activation levels of the leg muscles of the high sopite syndrome severity group participants were passively increased for maintaining balance and/or actively increased for performing the CTT. This will be further elaborated in the Discussion section. The increase in the normalised EMG_{SD} of the SOL and TA due to sopite syndrome severity equates to effect sizes of 1.20 (Cohen's *d*) and 0.85 (Cohen's *d*) respectively. The effect sizes suggest that the normalised EMG_{SD} of the SOL and TA of the high sopite syndrome severity group participants are 1.2 and 0.85 standard deviation respectively higher than the low sopite syndrome severity group participants.

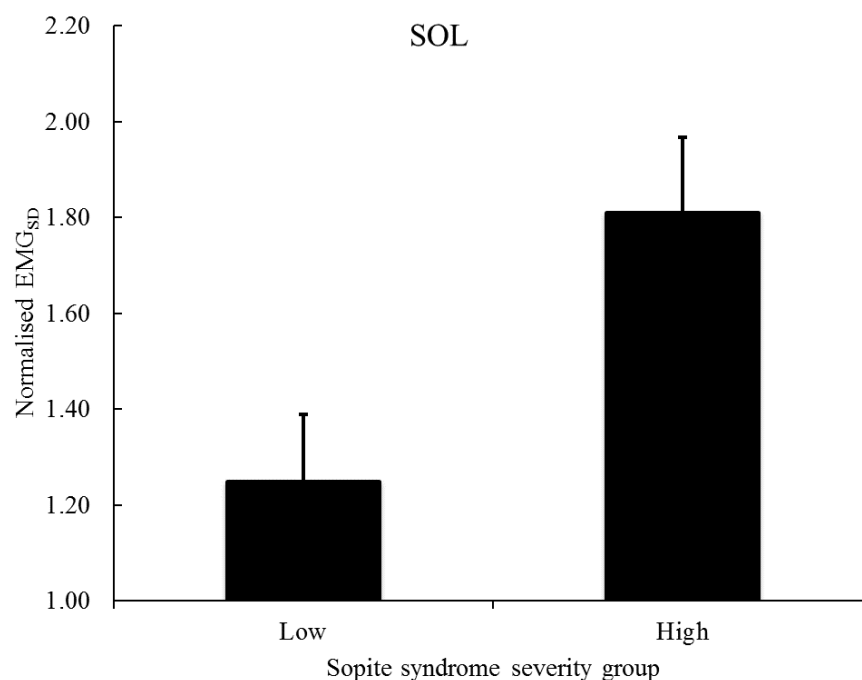


Figure 6.11. Normalised SOL EMG_{SD} (mean ± S.E.) across high (*N* = 9) and low (*N* = 11) sopite syndrome severity groups. Participants were performing CTT.

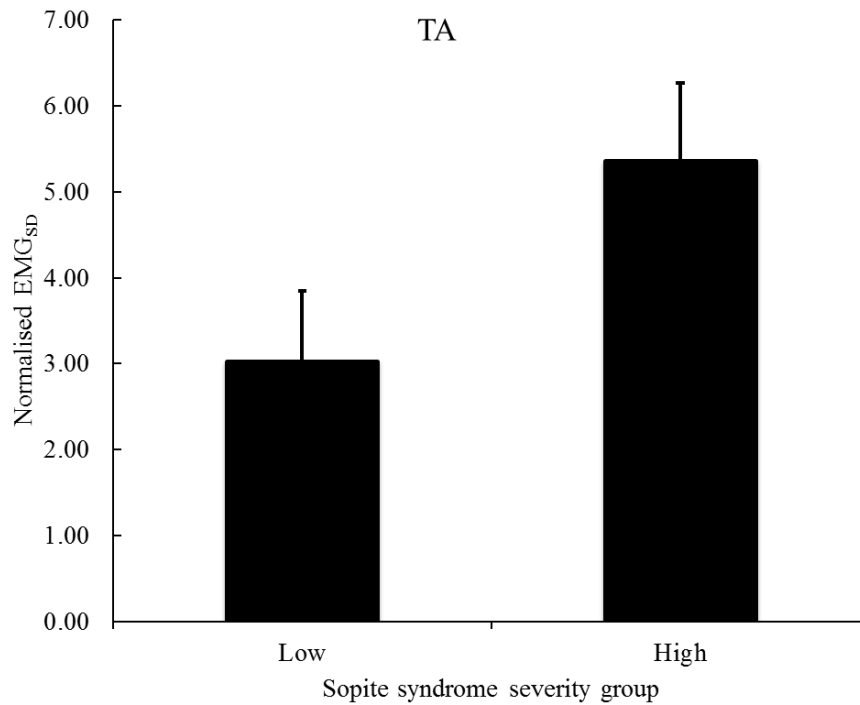


Figure 6.12. Normalised TA EMG_{SD} (mean \pm S.E.) across high ($N = 9$) and low ($N = 11$) sopite syndrome severity groups. Participants were performing CTT.

6.4.5 Effects of sopite syndrome on CTT performance under low-frequency, low-acceleration fore-aft motion conditions

Chapter 5 has investigated the effects of sopite syndrome on the CTT performance of the 40 participants who completed the CTT experiment: 20 participants under fore-aft motion conditions and another 20 under lateral motion conditions. The CTT performance was quantified by mean (\bar{r}), standard deviation (σ_r), and maximum (\hat{r}) resultant distances of a laser light dot from the centre of a target. Calculations of \bar{r} , σ_r , and \hat{r} were described in Chapter 4. The results of Chapter 5 have shown that the effects of sopite syndrome on the CTT performance of the 40 participants are significant. The high sopite syndrome severity group participants perform worse in the CTT than low sopite syndrome severity group participants.

Mixed-design three-way ANOVAs, with frequency and acceleration as within-subjects factors and sopite syndrome severity groups as between-subjects factor, shows that sopite syndrome severity significantly affect \bar{r} , σ_r , and \hat{r} of the 20 participants completed the experiment under fore-aft motion conditions, as shown in Table 6.12. The interaction between sopite-related score level and frequency and acceleration are not significant.

Table 6.12. A result summary of main and interaction effects of sopite syndrome severity on CTT performance of mixed-design three-way ANOVAs.

Performance measure	Effect	<i>F</i>	<i>p-value</i>
Mean resultant distance	Main effect of sopite syndrome severity	$F(1, 18) = 9.712$	$= 0.006$
	Interaction effect between frequency and sopite syndrome severity	$F(3, 54) = 0.703$	$= 0.554$
	Interaction effect between acceleration and sopite syndrome severity	$F(2, 36) = 1.087$	$= 0.348$
Standard deviation resultant distance	Main effect of sopite syndrome severity	$F(1, 18) = 11.052$	$= 0.004$
	Interaction effect between frequency and sopite syndrome severity	$F(3, 54) = 0.409$	$= 0.747$
	Interaction effect between acceleration and sopite syndrome severity	$F(2, 36) = 2.342$	$= 0.111$
Maximum resultant distance	Main effect of sopite syndrome severity	$F(1, 18) = 13.214$	$= 0.002$
	Interaction effect between frequency and sopite syndrome severity	$F(3, 54) = 0.694$	$= 0.560$
	Interaction effect between acceleration and sopite syndrome severity	$F(2, 36) = 2.944$	$= 0.065$

\bar{r} , σ_r , and \hat{r} of the high sopite syndrome severity group are greater than the low group, as shown in Figure 6.13 to Figure 6.15 respectively. The mean and standard deviation of the performance measures, that is, \bar{r} , σ_r , and \hat{r} are summarised in Table 6.13. These results indicate that, under low-frequency, low-acceleration fore-aft motion conditions, the high sopite syndrome severity group performs worse than the low sopite syndrome severity group. Differences in CTT performance between the high and low sopite syndrome severity groups equate to large effect sizes ranging from 1.4 (Cohen's d) to 1.6 (Cohen's d), as shown in Table 6.13.

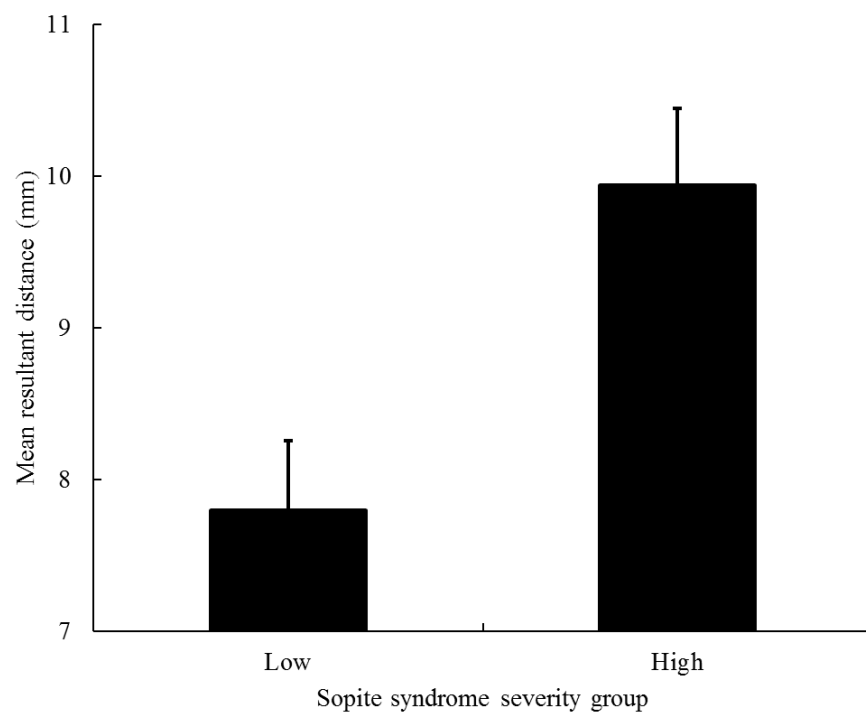


Figure 6.13. Mean resultant distance (mean \pm S.E.) across high ($N = 9$) and low ($N = 11$) sopite syndrome severity groups under low-frequency, low-acceleration fore-aft motion conditions.

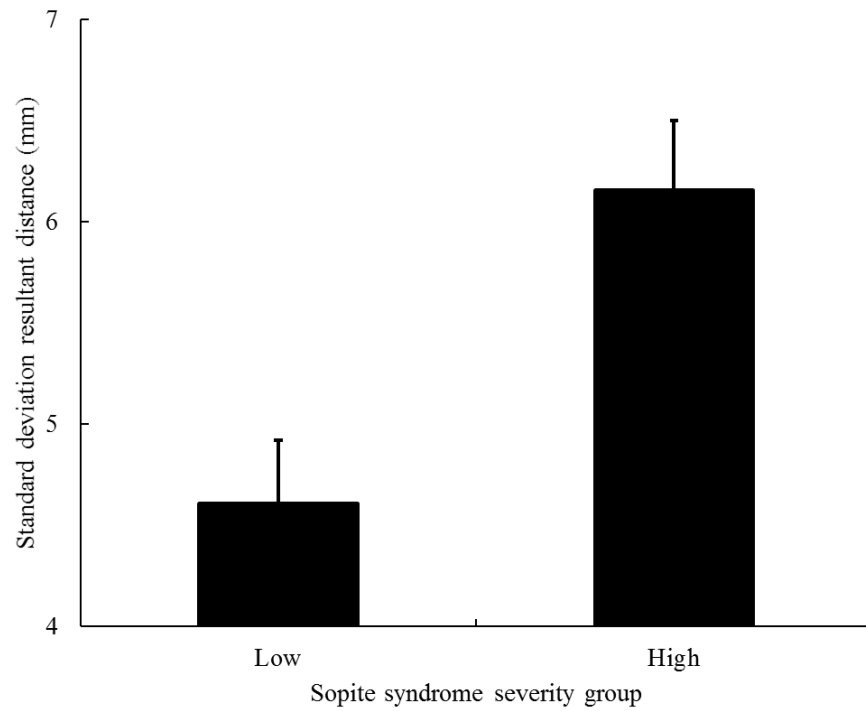


Figure 6.14. Standard deviation resultant distance (mean \pm S.E.) across high ($N = 9$) and low ($N = 11$) sopite syndrome severity groups under low-frequency, low-acceleration fore-aft motion conditions.

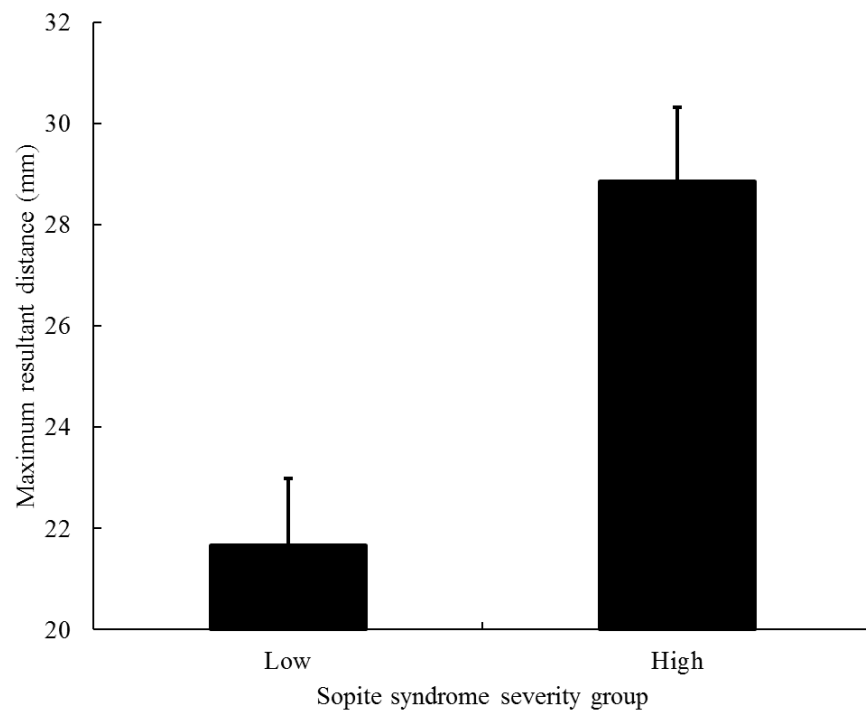


Figure 6.15. Maximum resultant distance (mean \pm S.E.) across high ($N = 9$) and low ($N = 11$) sopite syndrome severity groups under low-frequency, low-acceleration fore-aft motion conditions.

Table 6.13. Mean and standard deviation values of CTT performance of low and high sopite syndrome severity group participants.

Performance measure	Sopite syndrome severity	Mean (mm)	Standard deviation (mm)	Effect size (Cohen's <i>d</i>)
Mean resultant distance	Low (<i>N</i> = 11)	7.797	1.529	1.40
	High (<i>N</i> = 9)	9.938	1.530	
Standard deviation resultant distance	Low (<i>N</i> = 11)	4.609	1.035	1.49
	High (<i>N</i> = 9)	6.154	1.035	
Maximum resultant distance	Low (<i>N</i> = 11)	21.663	4.401	1.63
	High (<i>N</i> = 9)	28.855	4.401	

6.5 Discussion

Chapter 4 has shown that low frequency, low-acceleration motion degrades performance of a manual task. It is believed that the degradation was caused by the increase in inertial force due to acceleration effects and the frequency effects associated with the resonant characteristics of the human body. Chapter 5 has further investigated the effects of sopite syndrome on manual task performance. It was suggested that participants suffering sopite syndrome may exhibit a greater degree of postural instability, and this postural instability degrades task performance. Therefore, participants suffering more severe symptoms of sopite syndrome perform worse in the CTT than those suffering less severe symptoms of sopite syndrome. Furthermore, a previous study has suggested that low frequency, low acceleration motion can challenge balance; compensatory actions are needed for performing manual task in motion conditions (Burton et al., 2011). To provide supporting evidences for the findings and explanations presented in Chapters 4 and 5 and Burton et al.'s suggestions, this chapter investigated i) the effects of performing a manual task on the activation levels of the leg muscles; ii) the variations of leg muscle activation levels across acceleration and frequency; and iii) the effects of sopite syndrome severity on the activation levels of leg muscles and manual task performance.

6.5.1 Evidence for compensatory action

6.5.1.1 Effects of performing CTT

Performing the CTT significantly increases the activation level of SOL, as shown in Figure 6.1. The increase in the activation level of SOL is likely due to prolonged activations of SOL, which is a compensatory action carried out for performing a manual task. The prolonged activation of SOL may have stiffened the body, hence limiting the body sway for performing the CTT. Similarly, the participants may have activated other muscles to stiffen the body and limit body sway. Burton et al. (2011) suggested that individuals can compensate for the difficulty in maintaining balance in low-frequency, low-acceleration motion environments such that the motion conditions used in their study did not degrade manual task performance. Results of this chapter partly affirm Burton et al.'s (2011) suggestion. Although participants have attempted to compensate the effects of motion by increasing the activation levels of SOL, results of Chapter 4 suggested that the compensatory action can not completely overcome the effects of motion on performing the manual task. Hence, degraded manual task performance was measured even at 8 milli-g.

Performing the CTT reduces the activation level of TA, as shown in Figure 6.6. Since TA is primarily used to prevent the body from falling backward and usually remains silent when the perturbation is insufficient for challenging balance of human body (Fitzpatrick et al., 1992), the reduction in the activation level of TA suggested that the backward body sway was reduced when the participants were performing the CTT. This is likely to be a consequence of the increase in the activation level of SOL for performing the CTT, as shown in Figure 6.1, which stiffened the body and limited the body sway. Once the body is stiffened and stabilised, magnitude of backward body sway was decreased, resulting in the reduction of the activation level of TA. The reduction in the activation level of TA provides additional evidence showing that the participants have carried out a compensatory action for performing the CTT by increasing the activation level of SOL to limit body sway.

6.5.1.2 Interaction between performing the CTT and frequency on activation level of SOL

Section 6.5.1.1 has discussed that the participants may have attempted to limit body sway for performing the CTT by prolonged activation of SOL and/or other muscles. The prolonged activation of SOL then acts as a compensatory action such that performing the CTT increases the activation level of SOL. The interaction effect between performing the CTT and frequency on the activation level of SOL further supports the suggestion and provides additional details of the compensatory action.

Figure 6.4 shows the activation levels of SOL across frequency, with and without performing the CTT. In general, the activation level of SOL measured when the participants were performing the CTT is higher than the SOL EMG_{SD} measured when the participants were not performing the CTT. This is consistent with the suggestion that the compensatory action carried out for performing the CTT increases the activation level of SOL. It is notable that the differences in the activation levels of SOL between with and without performing the CTT situations vary as frequency increases from 0.125 Hz to 1 Hz. This is likely because the human body resonates near 0.5 Hz (Alexandrov et al., 2005; Alexandrov et al., 2001a, 2001b; Shin et al., 2006), which increases the body sway around 0.5 Hz.

Among the frequencies, the largest differences in the activation levels of SOL between with and without performing the CTT situations were found at either 0.125 Hz or 1 Hz. Since 0.125 Hz and 1 Hz are respectively well below and well above the resonant frequency of human body at around 0.5 Hz, the body sway at 0.125 Hz and 1 Hz is smaller than that at 0.5 Hz. The activation levels of SOL required for maintaining balance at 0.125 Hz and 1 Hz are low. Some activation capacity of SOL is idle at 0.125 Hz and 1 Hz. Therefore, the participants can use the idle activation capacity of SOL for performing the CTT, resulting in large increases in the activation levels of SOL at 0.125 Hz and 1 Hz. Since the participants use the idle activation capacity of SOL to carry out the compensatory action at 0.125 and 1 Hz, the task performance degradation at these frequencies are further alleviated.

In contrast, the body sway at 0.5 Hz is the most prominent due to the resonant characteristics of the human body, as discussed in Shin et al. (2006). Activation of SOL is already at a heightened level primarily used to maintain postural stability at 0.5 Hz. The idled activation capacity of SOL at 0.5 Hz available for carrying out the compensatory action is limited. Therefore, performing the CTT elicited a comparatively small increase in activation level of SOL. Since the idle activation capacity of SOL at 0.5 Hz is limited, the compensatory action carried out for performing the CTT are not effective. This also contributes to the largest manual task performance degradation measured at 0.5 Hz.

6.5.1.3 Interaction between performing the CTT and acceleration on activation level of TA

Since the TA is generally activated to adjust backward body sway when balancing is jeopardised, the activation level of TA reflects the stability level of the human body. Results of this chapter show that the interaction effects between performing the CTT and acceleration significantly affect the activation level of TA. The interaction effect can actually demonstrates the stability level of the human body for performing the CTT across acceleration from 8 milli-g to 30 milli-g. Figure 6.9 shows the activation levels of TA across acceleration when the participants were or were not performing the CTT. The figure shows that, without performing the CTT, the increasing rate of the activation level of TA increases as acceleration increases from 8 milli-g to 30 milli-g. At 8 milli-g, the activation levels of TA when the participants were or were not performing the CTT are comparable. This suggests that the stability of the participants with and without performing the CTT are similar at 8 milli-g. In contrast, at 30 milli-g, the activation levels of TA when the participants were not performing the CTT are higher than those when the participants were performing the CTT. The results demonstrate that the body sway when the participants were not performing the CTT is larger than that when the participants were performing the CTT. This affirms that compensatory actions were carried out to stabilise the body and limit the backward body sway for maintaining balance when performing the CTT.

6.5.2 Evidences for increased inertial forces – effects of acceleration on activation levels of SOL and TA

While Burton et al. (2011) suggested that increase in acceleration magnitude did not significantly degrade manual task performance, Chapter 4 has shown that manual task performance is degraded as acceleration increases from 8 milli-g to 30 milli-g. Chapter 4 has discussed that the degradation was caused by the increase in inertial force acting on the human body as acceleration increases from 8 milli-g to 30 milli-g. The increase in inertial force can increase body sway, disrupt balance, induce visual impairment, increase vibration breakthrough, and/or trigger motion sickness or sopite syndrome, which in turn degrade manual task performance.

As expected, the activation levels of SOL and TA increase monotonically as acceleration increases from 8 milli-g to 30 milli-g, as shown in Figure 6.2 and Figure 6.7 for SOL and TA respectively. Since the SOL and TA are activated for maintaining balance, the increases in the activation levels of SOL and TA affirm that the balance of the participant were further jeopardised as acceleration increases from 8 milli-g to 30 milli-g.

Under quiet bipedal standing, adjusting activation of SOL is generally adequate for balancing (Winter, 1995). SOL is usually activated even without any perturbation. In contrast, TA is usually silent or at a low level of activation when the perturbation is insufficient to jeopardise balance (Fitzpatrick et al., 1992); TA is not usually responsible for maintaining an upright stance under normal circumstance. This chapter shows that effect sizes of acceleration on SOL and TA activation levels equate to 0.85 and 2.22 for SOL and TA respectively. The effect size of acceleration on the activation levels of TA is much greater than that on the activation levels of SOL. Activations of TA are needed to maintain balance. This is another piece of evidence to support that the increase in acceleration significantly disrupts the balance of participants.

6.5.3 Evidence for resonant characteristic of human body – effects of frequency on activation levels of SOL and TA

SOL and TA EMG_{SD} exhibit a nonlinear relationship with frequency, with an increase in activation levels from 0.125 Hz up to 0.25 or 0.5 Hz, followed by a drop at 1 Hz. This trend is consistent with the relationships between CTT performance and frequency as shown in Chapter 4. Chapter 4 has discussed the nonlinear relationship between CTT performance and frequency which is believed to be due to the resonant characteristics of human body (Shin et al., 2006). These characteristics may cause body sway near the resonant frequency to be higher than that at other frequencies, hence producing a greater interruption to performing the CTT. The nonlinear relationships between EMG_{SD} and frequency, as shown in Figure 6.3 and Figure 6.8 for SOL and TA respectively, offer further supports to these explanations.

As noted above, SOL and TA are leg muscles responsible for maintaining balance and resisting body sway. In general, the activation levels of SOL and TA required for maintaining balance and resisting body sway increase as body sway increases. Therefore, the variation of body sway magnitude across frequency is likely to be similar to those of the EMG_{SD} measure in this study. Furthermore, EMG_{SD} peaking at 0.25 or 0.5 Hz were likely caused by the increased body sway due to the resonant characteristic of human body (Shin et al., 2006). Since the variation patterns of EMG_{SD} across frequency are similar to the pattern associated with CTT accuracy, the worsened CTT accuracy around 0.25 and 0.5 Hz is most likely caused by increased body sway.

6.5.4 Interaction between acceleration and frequency

The interaction effects between acceleration and frequency significantly affect both the activation of SOL and TA. The nonlinear relationship between EMG_{SD} and frequency at 30 milli-g motion conditions is the most prominent among the test accelerations for both SOL and TA. This trend is consistent with the interaction effect of frequency and acceleration on CTT performance presented in Chapter 4.

6.5.5 Relationship between activation levels of leg muscles, symptoms of sopite syndrome, and CTT performance

When the participants were performing the CTT, the normalised EMG_{SD} of the leg muscles of the high sopite syndrome severity participants was higher than low sopite syndrome severity participants, as shown in Figure 6.11 and Figure 6.12 for the normalised EMG_{SD} of SOL and TA respectively. It is hypothesised that leg muscle activation levels of high sopite syndrome severity group participants are passively increased for maintaining balance and/or actively increased for performing the CTT. Results of the normalised EMG_{SD} of the SOL and TA measured when the participants were not performing the CTT may provide hints on this hypothesis. When the participants were not performing the CTT, the difference in the normalised EMG_{SD} of the SOL and TA between the high and low sopite syndrome severity groups were not significant. The results suggest that, without performing the CTT, the motion effects on leg muscle activation levels responsible for maintaining balance of both high and low sopite syndrome severity group participants are likely to be similar. Thus, when the participants were performing the CTT, the high sopite syndrome severity group participants should have actively increased activation levels of leg muscles for performing the CTT rather than maintaining balance.

Chapter 5 has investigated the effects of sopite syndrome on the CTT performance of 40 participants who completed the CTT experiment: 20 participants under fore-aft motion conditions and another 20 participants under lateral motion conditions. The results of Chapter 5 have shown that the high sopite syndrome severity group participants perform worse in the CTT than low sopite syndrome severity group participants. This chapter reanalysed the CTT performance of the 20 participants who completed the CTT under fore-aft motion conditions and presented the results in Section 6.4.5. The results of the reanalyses, as shown in Figure 6.13 to Figure 6.15, affirm that the high sopite syndrome severity group participants perform worse in the CTT than low sopite syndrome severity group participants. This may be because the high sopite syndrome severity group participants may have actively increased their leg muscles which in turn, distracted and/or diverted attention from aiming a laser light dot at the centre of a target, resulting in degraded task performance.

Motion sickness has been postulated to be the result of prolonged postural instability (Riccio and Stoffregen, 1991). The postural instability does not have to be a frank loss of control but can be a degraded stability that may lead to increases in body sway preceding or at the onset of motion sickness that can persist over a long period of time (Stoffregen and Smart, 1998). Although the results of this chapter show that, without performing the CTT, the normalised leg muscle activation levels responsible for maintaining balance of both high and low sopite syndrome severity group participants are similar, the results cannot affirm whether the high sopite syndrome severity group participants sway more than the low sopite syndrome severity group participants under motion conditions. This is because sway was not measured directly. Similarly, when the participants were performing the CTT, whether the high sopite syndrome severity group participants would have swayed more than the low sopite syndrome severity group participants is yet to be determined, although the normalised activation levels of the high sopite syndrome severity group participants were higher than the low sopite syndrome severity group participants.

Nevertheless, this chapter offers some evidence to support a correlation between sopite syndrome severity and increased activation levels for maintaining balance to perform the CTT. The underlying relationship however has yet to be fully explored and understood. One possible manifestation of such a relationship is that the high sopite syndrome severity group participants increase the activation levels of the leg muscle for performing the CTT because they do not possess effective strategies for maintaining postural stability, triggering sopite syndrome. The possible manifestation may happen in the reverse sequence such that exposure to the motion triggers sopite syndrome. As a result, participants suffering sopite syndrome sway more and then require higher activation levels of leg muscle for performing the CTT than the relatively unaffected participants.

6.5.6 Limitations

Although the results indicate that when participants were performing the CTT, the leg muscle activation levels responsible for maintaining balance of the high sopite syndrome severity participants was higher than low sopite syndrome severity participants, whether the high sopite syndrome severity group participants swayed more than the low sopite syndrome severity group participants under motion conditions is not yet fully understood. Measurement of body sway when participants were performing the CTT is required to determine whether the increased leg muscles activation levels and decreased CTT performance are caused by increased body sway.

Section 6.5.5 has discussed the underlying relationships between sopite syndrome, body sway, and increased activation levels for performing the CTT have yet to be fully explored and understood. The relationships may be confirmed by ascertaining the occurrence sequence of sopite syndrome, increased body sway, and increased leg muscle activation levels. The current study, however, has recorded sopite syndrome severity at the beginning and the end of the experiment. Therefore, no information is available to reveal how the sopite syndrome severity developed throughout the experiment. Furthermore, the current study measured leg muscle activities but lacks information on body sway throughout the experiment for comparisons. Measurement of sopite syndrome severity and body sway information throughout the experiment are needed to provide more revealing information.

The current study was conducted under fore-aft motion conditions. Chapters 4 and 5 showed that the effects of lateral motion on manual task performance and occurrence of symptoms of sopite syndrome were not significantly different from the effects of fore-aft motion. Therefore, the activation behaviors in the leg muscles responsible for the postural stability in the lateral direction may also be similar to those in the fore-aft direction. Further research is needed to provide evidence to support the prediction.

6.6 Conclusions

This chapter has investigated i) the effects of performing a continuous tracking task (CTT) on the activation levels of the leg muscles, soleus (SOL) and tibialis anterior (TA) involved in maintaining balance in the fore-aft direction; ii) the variations of leg muscle activation levels across acceleration and frequency; and iii) effects of sopite syndrome severity on the activation levels of the leg muscles to provide supporting evidence for the findings and explanations presented in Chapters 4 and 5 and demonstrate whether compensatory action was carried out in performing a manual task.

The significant main and interaction effects of performing the CTT on the activation of the leg muscles involved in maintaining balance support that compensatory actions were carried out for performing the manual task. Participants increased the activation level of the SOL for performing the CTT by prolonged activation. The prolonged activation of the SOL, as a compensatory action, stiffened the ankles and, presumably, limited body sway for performing the CTT. Meanwhile, performing the CTT reduced the activation level of the TA. Since the activation level of the TA decreased as the magnitude of backward body sway decreased, the reduced activation level of the TA affirms that the prolonged activation of the SOL effectively stiffens and stabilised the body and limited body sway for performing the CTT.

The significant interaction effect between performing the CTT and frequency on the activation levels of the SOL affirms the participants carried out compensatory actions by increasing activation of the SOL and provides additional details of the compensatory action across frequency. At 0.125 Hz and 1 Hz, where the frequencies are well below and well above the resonant frequency of the human body at around 0.5 Hz (Shin et al., 2006), the body sway at 0.125 Hz and 1 Hz was smaller than that at 0.5 Hz. The activation levels of the SOL required for maintaining balance at 0.125 Hz and 1 Hz are low. Some activation capacity of the SOL is idle at 0.125 Hz and 1 Hz. As such the participants can use the idle activation capacity of the SOL for performing the CTT, resulting in large increases in the activation levels of the SOL at 0.125 Hz and 1 Hz when the participants were performing the CTT. On the other hand, the significant interaction effects between performing the CTT and acceleration on the activation level of the TA affirm that compensatory actions were carried out to stabilise the body and limit the backward body sway for maintaining balance, particularly at high acceleration magnitude.

The activation levels of the SOL and TA increase as the acceleration increased from 8 milli-g to 30 milli-g. The increases in the activation levels were needed to resist the body sway induced by the increase in inertial force across acceleration. The activation levels of the SOL and TA varied nonlinearly across frequency. The nonlinear relationships between the activation levels of the leg muscles and frequency presented in this chapter are similar to the nonlinear relationships between CTT performance and frequency presented in Chapter 4. The results support that the resonant characteristic of the human body is a cause of manual task performance degradation in low frequency, low-acceleration motion environments.

When the participants were performing the CTT, motion effects on the normalised activation levels of the SOL and TA of high sopite syndrome severity group was significantly higher than for the low sopite syndrome severity group. In contrast, when the participants were not performing the CTT, the motion effects on the normalised leg muscle activation levels were similar for both high and low sopite syndrome severity groups. Therefore, the high sopite syndrome severity group participants should have actively increased the activation levels of the leg muscles for performing the CTT rather than maintaining balance. The actively increased leg muscle activation levels may have been a distraction and diverted participants' attention from aiming a laser light dot at the centre of a target, resulting in worse CTT accuracy.

Results of this chapter may tie in with the postural instability theory which hypothesises that “animals become sick in situations in which they do not possess (or have not yet learned) strategies that are effective for the maintenance of postural stability” (Riccio and Stoffregen, 1991, p. 195). The increased activation levels of the high sopite syndrome severity group participants suggest that the participants may not be able to effectively maintain postural stability, resulting in degraded manual task performance. However, the underlying relationship has yet to be fully explored and understood. One possible manifestation of such a relationship is that the high sopite syndrome severity group participants increase the activation levels of their leg muscles for performing the CTT, triggering sopite syndrome. The relationship can also occur in the reverse order. Further studies are needed to explore and understand this relationship.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS

7.1 Conclusions

Assessing the acceptability of wind-induced building motion is a vital requirement for designing habitable buildings. Over the last 50 years, researchers have conducted field studies and surveys of occupants in buildings subjected to strong wind or artificial excitations, and motion simulator studies to investigate the human responses in real or simulated wind-excited building environments (for example Chen and Robertson, 1972; Goto, 1983; Hansen et al., 1973; Tamura et al., 2006). Results of these studies have mainly focused on perception thresholds and/or tolerance to wind-induced building motion. The current criteria and recommendations for assessing the acceptability of wind-induced building motion were established largely based on the perception thresholds and/or tolerance to wind-induced building motion determined from the previous studies (for example Architectural Institute of Japan, 2004; International Organization for Standardization, 2007). Recent research has shown that wind-induced building motion can degrade work performance of building occupants (Lamb et al., 2014). Therefore, the current criteria and recommendations do not adequately consider the effects of wind-induced building motion on manual task performance for the design of building used for general purposes by the general population.

Little is known about the effects of low-frequency, low-acceleration motion on manual tasks performance. Few studies have investigated the effects (for example Burton et al., 2011; Goto et al., 1990; Irwin and Goto, 1984). The findings of these studies are inconclusive. One of these studies found that acceleration and/or frequency did not affect manual task performance (Burton et al., 2011) while the others found that the motion can degrade manual task performance. These inconclusive findings may be attributed to the characteristics of participants, manual tasks, motion, or a combination of these factors. In addition, these studies did not establish any relationships between manual task performance and motion frequency and acceleration magnitudes, nor determined the potential causes that adversely affect manual task performance.

Previous studies have recognised that wind-induced building motion could provoke salient symptoms of motion sickness, such as nausea and vomiting (for example Burton et al., 2005; Goto, 1983; Hansen et al., 1973). The incidence of motion sickness is likely to occur at high acceleration magnitudes and is hence relevant only to extreme wind events. Recent studies showed that wind-induced building motion at low-acceleration magnitudes can provoke sopite syndrome in many building occupants (Lamb et al., 2013, 2014; Walton et al., 2011). Sopite syndrome is a “symptom-complex centering around drowsiness” (Graybiel and Knepton, 1976, p. 873). It also includes symptoms such as lassitude, lethargy, mild depression, which reduce occupants’ ability to focus on an assigned task (Matsangas and McCauley, 2014). Since low-acceleration, wind-induced building motion occurs far more frequently than extreme windstorms, the incidence of sopite syndrome becomes an important issue related to human responses to wind-induced building motion. While Lamb et al. (2014) investigated the relationship between the severity of sopite syndrome and subjective work performance and cognitive performance, no study has investigated the effect of sopite syndrome on manual task performance under building motion conditions. Hence further studies are warranted to consider the effects of sopite syndrome on manual task performance.

To address the effects of low-frequency, low-acceleration motion and sopite syndrome on manual task performance, a series of motion simulator experiments was conducted to investigate the effects of low-frequency, low-acceleration motion on manual task performance. Twelve sinusoidal motion conditions were reproduced for both fore-aft and lateral directions using three acceleration magnitudes (8, 16, and 30 milli-g) and four frequencies (0.125, 0.25, 0.5, and 1 Hz). A continuous tracking task (CTT) was used as a paradigm to quantify the effects of low-frequency, low-acceleration motion on manual task performance. The CTT required participants to hold a laser pointer in their dominant hand, and aim a laser light dot as close as possible to the centre of a target. The CTT was chosen because a study showed that the effects of vertical translational motion on a continuous tracking task was more significant than on a discrete tracking task (McLeod and Griffin, 1988). Another advantage is that the CTT does not involve any complicated scoring system that may mask the effects of acceleration and frequency on manual task performance. Furthermore, many office workers are now requesting standing desks as standing improves cardiovascular health and reduces back ache. It is likely that the effects of wind-induced building motion on manual task performance of standing occupants may increase. Therefore, using the CTT to evaluate manual task performance is a direct and effective approach for determining the effects of acceleration and frequency on manual task performance. The CTT is representative of real life situations that require a standing building occupant who carries out a continuous task without any support for stabilising the human body, such as a standing occupant writing on a white board and a standing presenter using a laser pointer to point at a screen. The mean, standard deviation, and maximum resultant distances are the measures for CTT performance. Twenty participants completed the experiment under fore-aft motion conditions and another 20 participants under lateral motion conditions. A Motion Sickness Assessment Questionnaire (MSAQ) was used to measure motion sickness severity, in particular the severity of sopite syndrome, due to exposure to low-frequency, low-acceleration motion (Gianaros et al., 2001).

The results show that manual task performance was degraded even at the lowest test acceleration magnitude of 8 milli-g. Acceleration of this magnitude however was considered satisfactory for the evaluation of habitability of ranges of wind-excited office buildings that have fundamental natural frequencies between 0.125 and 0.5 Hz and residential buildings that have fundamental natural frequencies between 0.125 and 0.2 Hz (International Organization for Standardization, 2007). Both acceleration and frequency were found to contribute to the observed performance degradations. The contributions of acceleration to the manual task performance degradations are greater than frequency. Acceleration shows a strong inverse relationship with manual task performance; manual task performance decreases as the acceleration increases. The acceleration effect is attributable to an increase in inertial force, which can, in turn, induce visual impairment, disrupt balance, increase vibration breakthrough, and trigger motion sickness or sopite syndrome. In contrast, frequency has a complex nonlinear relationship with manual task performance. The worst performance was measured at 0.5 Hz among the tested frequencies ranging from 0.125 to 1 Hz. The effect of frequency is associated with the frequency response characteristic of the human body. Body sway increases as frequency approaches the resonant frequency of a standing human, which occurs at near 0.5 Hz.

The current serviceability criteria or recommendations do not adequately consider the effects of wind-induced building motion on manual task performance in buildings occupied by the general population (for example International Organization for Standardization, 2007). A comparison between performance degradation and the acceleration criteria of ISO 10137:2007 has shown that using this criteria to assess the acceptability of wind-induced building motion does not ensure the performance of manual tasks are unaffected.

The incidence of sopite syndrome and its effects on manual task performance have been investigated. Changes in sopite syndrome severity due to the exposure to the 12 motion conditions were measured using the Motion Sickness Assessment Questionnaire (MSAQ). Under the combined influence of approximately 30 minutes exposure to the 12 motion conditions, some form of motion sickness, in particular sopite syndrome, was provoked in most participants. The results affirmed that motion sickness occurring in wind-excited buildings mostly manifests as symptoms of sopite syndrome (Lamb et al., 2014; Walton et al., 2011).

Manual task performance has an inverse relationship with sopite syndrome severity: individuals who exhibited mild to severe sopite syndrome performed worse than relatively unaffected individuals. Sopite syndrome imposes discomfort and stress on affected participants and lowers their motivation to perform the manual task. Body sway in response to motion is further exacerbated for participants who exhibited sopite syndrome, causing postural instability that affected task performance. These adverse effects associated with sopite syndrome contributed to degrade the manual task performance for affected participants.

The results suggest that the degradation of manual task performance is associated with body sway due to the effects of acceleration, frequency, and sopite syndrome. Furthermore, previous studies have suggested that individuals may carry out action to compensate for the effects of motion. Hence measurements were taken to determine activation levels of lower leg muscles, in particular soleus (SOL) and tibialis anterior (TA) involved in maintaining balance, to investigate the effects of performing the CTT, acceleration, frequency, and sopite syndrome.

The results show that participants attempted to stiffen and stabilise the body and limit body sway to compensate the effects of motion for performing the CTT. The compensatory action manifested primarily as an increase in the activation levels of SOL. Interestingly, performing the CTT reduced the activation levels of TA which is primarily used to prevent the body from falling backward and usually remains silent when the perturbation is insufficient to challenge balance.

The activation levels of lower leg muscles monotonically increase with acceleration and have a highly non-linear relationship with frequency. These variations are similar to CTT performance variation across acceleration and frequency respectively. The results show that the degradations of manual task performance are associated with an increase in inertial force and the resonant characteristic of the human body that altered the sway characteristics of the human body.

When the participants were performing the CTT, the activation levels of lower leg muscles of the high sopite syndrome severity group are higher than the low sopite syndrome severity group. This suggests that participants suffering sopite syndrome consciously intervened with higher activation levels of leg muscles to perform the CTT than the relatively unaffected participants. The conscious increase in leg muscles activation levels may distract and/or divert attention from performing the CTT, further degrading the manual task performance.

7.2 Recommendations for future work

While this thesis has investigated the effects of low-frequency, low-acceleration motion on manual task performance and identified a number of possible mechanisms that caused the manual task performance degradation, there are a number of limitations that need to be addressed by further studies.

7.2.1 Minimum acceleration magnitudes that degrade manual task performance

This thesis has investigated the effects of low-frequency, low-acceleration motion on manual task performance at acceleration magnitudes of 8, 16, and 30 milli-g and at frequencies of 0.125, 0.125, 0.5, and 1 Hz. The motion can degrade manual task performance by 26% even at the low acceleration magnitudes of 8 milli-g, as shown in Figure 7.1. The minimum acceleration magnitudes that would cause performance degradation is unknown. Jeary et al. (1988) conducted a study in an artificially excited building to investigate the effects of motion on task performance. The study was conducted at a frequency of approximately 1.6 Hz and at peak acceleration magnitudes of 1 milli-g or 4 milli-g. Jeary et al. found that the motion did not degrade task performance. This suggests the minimum acceleration magnitudes that would cause performance degradation may exist between 4 and 8 milli-g. It is also suggested to extend the lower limit of the frequency range to 0.06 Hz to cover a larger range of frequency that are applicable for buildings with greater height. A proposed acceleration and frequency range for further studies is shown in Figure 7.1. Further studies may use the experimental protocol of this thesis to investigate the effects of motion of the proposed acceleration and frequency range.

It is noteworthy that the mechanisms causing manual task performance degradation may be different for various acceleration and/or frequency ranges (McLeod and Griffin, 1988). While this thesis has investigated the effects of acceleration, frequency, and sopite syndrome on manual task performance, performance degradation may be caused by other mechanisms, such as visual impairment, disrupted balance, and vibration breakthrough in the proposed acceleration (below 8 milli-g) and frequency (from 0.06 Hz to 1 Hz) range.

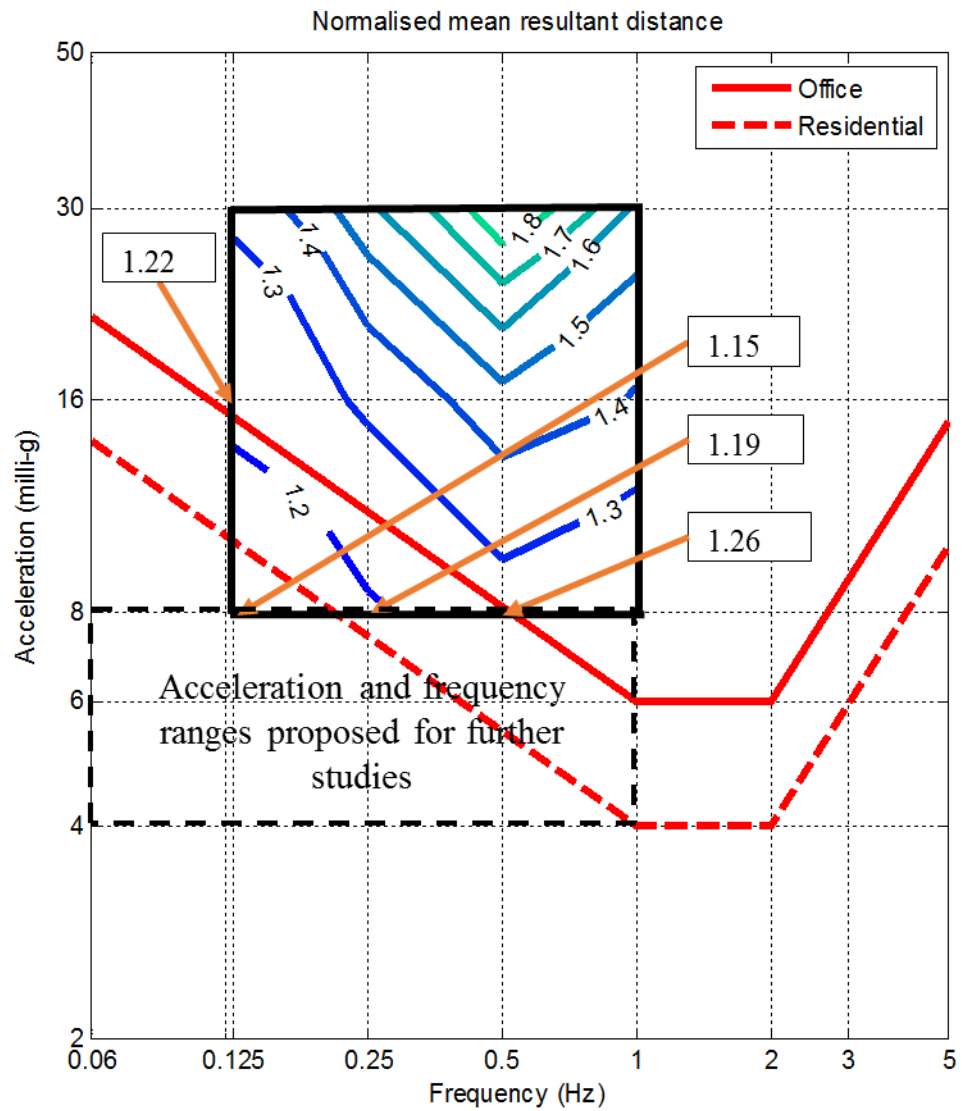


Figure 7.1. An acceleration and frequency range proposed for further studies.
(revised based on Figure 4.17).

7.2.2 Manual task performance degradation contours for various probability levels

AIJ-GEH-2004 proposed five frequency-dependent peak acceleration curves for perception probabilities of 10% to 90% (Architectural Institute of Japan, 2004). The peak acceleration curves for the perception probabilities were determined by fitting perception thresholds of participants with log normal distributions (for example Chen and Robertson, 1972; Tamura et al., 2006). Using the frequency-dependent peak acceleration curves of AIJ-GEH-2004, building owners and/or designers can choose the peak acceleration curve of an appropriate level of perception probability for habitability evaluation at their own discretion on building performance. This thesis has presented contours of average manual task performance degradation of all participants, as shown in Figure 7.1. Additional studies can determine manual task performance degradation contours of various probability levels using an appropriate probability distribution, such as the log normal distribution.

Furthermore, Isyumov (1993, 1995) proposed a set of acceptability criteria that are independent of frequency. Isyumov justified the use of frequency independent acceptability criteria based on Shioya et al. (1992) who found that the 2nd percentile perception thresholds in the frequency range between 0.125 to 0.315 Hz were nearly constant. Further studies are needed to determine whether a similar trend would appear in manual task performance degradation contours of different probability levels.

7.2.3 Effects of low-frequency, low-acceleration motion on other manual tasks

This thesis used a continuous tracking task (CTT) as a paradigm to investigate the effects of low-frequency, low-acceleration motion on manual task performance. The CTT required standing participants to hold a laser pointer in their dominant hand, and aim a laser light dot as close as possible to the centre of a target. Apparently, the CTT is significantly different from many manual tasks carried out in real building environments, such as sitting at a desk and working on a computer. The differences may be due to the difficulty of the manual tasks, posture, and the dexterity required to undertake the task. The results of this thesis may not be directly applicable to other types of manual tasks undertaken in real building environments. Applicability of the results depends on the similarity between the manual tasks carried out in a real building environment and the CTT used in the current thesis.

This thesis has shown that performance degradations of the CTT are due to the effects of inertial force, the resonant characteristics of the human body, and sopite syndrome. However, degradations of other manual tasks may be caused by other mechanisms. For example, while an individual sits at a desk and works on a computer using a mouse, the individual may use their hand as a support to minimise the body sway induced by wind-induced building motion. The armrest and/or backrest of a chair may also provide additional support that alters the resonant characteristic of the human body. Future research is required to investigate the extent to which the findings of this thesis are applicable to other types of manual tasks that typically occur in real building environments. The research may also generalise the degradation characteristics of the manual tasks according to the mechanisms causing the degradations.

7.2.4 Relationships between manual task performance, sopite syndrome severity, and motion characteristics

It is well-known that motion sickness incidence (MSI) is related to motion characteristics including duration of exposure, frequency, and acceleration (for example McCauley et al., 1976; Money, 1970; Reason and Brand, 1975). McCauley et al. (1976) showed that MSI, defined as the percentage of participants experiencing vomiting, increased with an exposure duration of up to two hours, as shown in Figure 7.2. McCauley et al. (1976) also established the relationships between MSI, RMS acceleration magnitudes ranging from 111 to 333 milli-g, and frequencies from 0.083 to 0.7 Hz for an exposure duration of two hours, as shown in Figure 7.3. The results showed that the greatest MSI was measured at a frequency of 0.167 Hz. It is noteworthy that the acceleration magnitude range was significantly higher than that of wind-induced building motion. Therefore, the results are not directly applicable for the design of wind-excited buildings.

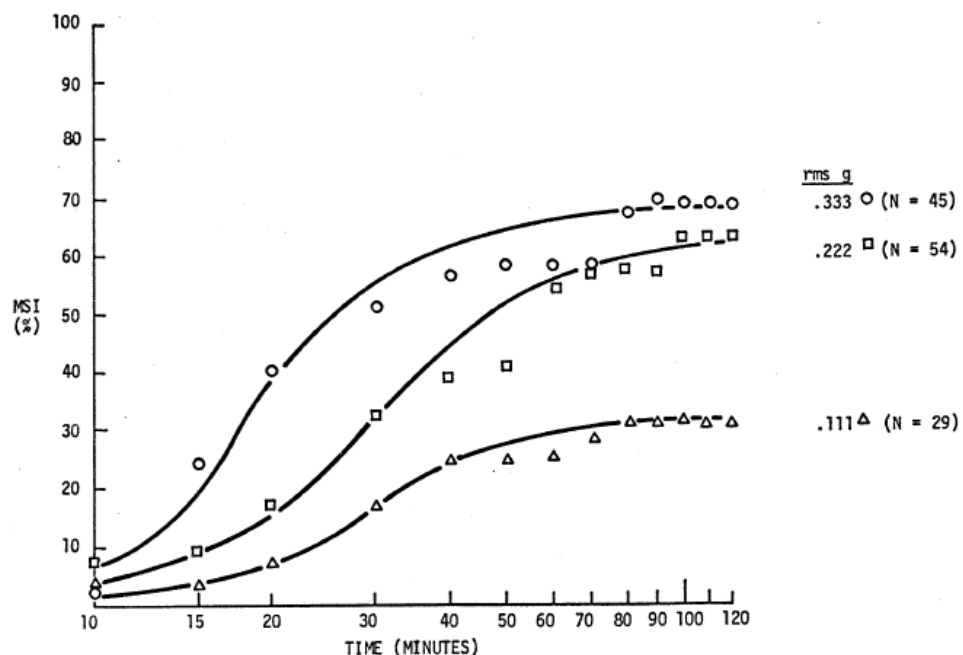


Figure 7.2. Motion sickness incidence of three independent groups of individuals measured at 0.25 Hz and at RMS accelerations of 111, 222, and 333 milli-g across time (reproduced from Figure 7 of McCauley et al., 1976).

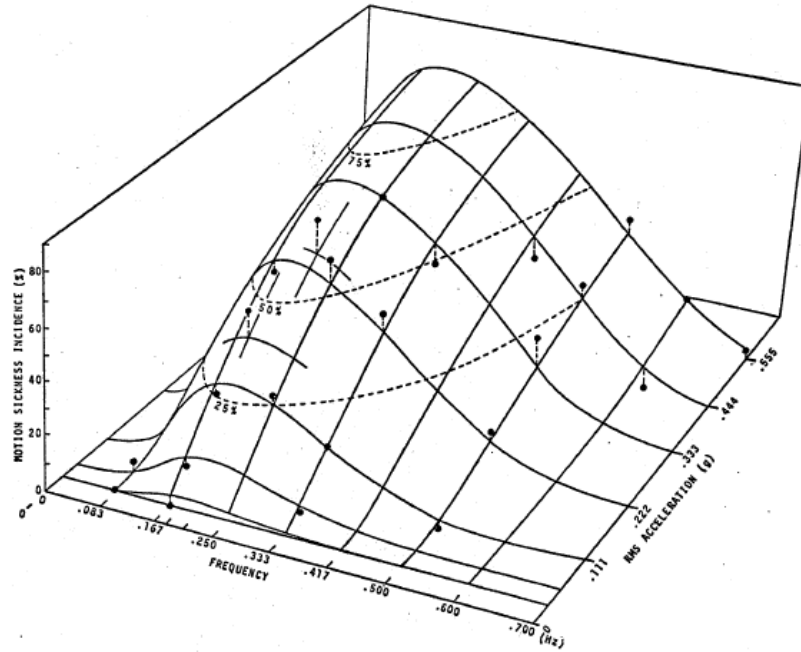


Figure 7.3. Motion sickness incidence as a function of acceleration and frequency (reproduced from Figure 8 of McCauley et al., 1976). Motion sickness incidence was defined as percentage of individuals vomiting within 2 hours of exposure to vertical sinusoidal motion.

Chapter 5 showed that exposure to 12 motion conditions for a duration of approximately 30 minutes in total was sufficient to cause some forms of motion sickness in most participants, particularly symptoms of sopite syndrome. Since the participants were influenced by the combined effects of the 12 motion conditions reproduced by four frequencies and three acceleration magnitudes, the effects or contributions of each motion condition on changes in sopite syndrome severity are unknown. Furthermore, the durations required to provoke the same changes in sopite syndrome severity between the motion conditions may be different.

Further studies are required to investigate the effects of frequency, acceleration, and exposure duration on changes in sopite syndrome severity. The studies may expose participants to only one motion condition in each experimental session and measure changes in sopite syndrome severity at a fixed time interval across a long exposure duration. From that, plots between changes in sopite syndrome severity, frequency, and acceleration for various exposure durations may be generated in a form similar to that of Figure 7.3. The studies may also fit the changes in sopite syndrome severity with a probability distribution to determine the changes in sopite syndrome severity across frequency and acceleration magnitudes at particular percentiles of the general public. The studies may be conducted at frequencies between 0.06 Hz and 1 Hz and acceleration magnitudes between 4 and 30 milli-g, as proposed in Section 7.2.1 . Furthermore, McLeod and Griffin (1993) found that the duration effects of exposure to high frequency (4 Hz), high acceleration (weighted acceleration of 1.4 ms^{-2} r.m.s.) motion on task performance were significant. Therefore, future studies could also measure manual task performance at a fixed time interval in each motion condition to correlate task performance with changes in sopite syndrome severity, frequency, acceleration, and exposure duration.

7.2.5 Effects of narrow-band random motion on manual task performance and incidence of sopite syndrome

In narrow-band random motion, the acceleration magnitudes of motion cycles may change suddenly, depending on the peak factor of the random motion. The effects of the unpredictability of the sudden change in the acceleration magnitude of random wind-induced building motion on manual task performance are expected to be significant. However, Burton et al. (2011) reported that bi-directional, narrow-band random motion did not degrade manual task performance; the findings were neutral. Chapter 4 discussed the possible causes for the neutral findings reported by Burton et al. (2011). One of the possible causes was the uses of a discrete manual task (a shooter game task) and bi-directional, narrow-band random motion in the study. It is suspected that the probability of the simultaneous occurrence of the relatively high acceleration magnitude motion cycles and the appearance of a target in the shooter game task was low. As such, participants of the study may have performed the shooter game task at relatively low acceleration for a majority of the time, resulting in the neutral findings.

A continuous manual task such as the CTT used in this thesis may be sensitive to reflect the effects of the sudden change in the acceleration magnitudes of random motion. This thesis, however, only used sinusoidal motion to simulate a short period (64 seconds) of wind-induced building motion that contained multiple cycles of relatively similar amplitude, to replicate motion that occurs in a typical burst of wind-induced building motion. The thesis did not therefore investigate the effects of a sudden change in the motion amplitude of random or high peak factor random wind-induced building motion. Furthermore, Burton et al. (2005) suspected that the unpredictability of the sudden change in the acceleration magnitude of the random motion was responsible for the increase in the reports of nausea in controlled laboratory environments. Future studies are warranted to consider the effects of the random motion on manual task performance and/or incidence of motion sickness.

7.2.6 Body sway measurements

The results of Chapter 4 suggest that the effects of sopite syndrome and the effects of frequency associated with the resonant characteristics of the human body significantly degrade the manual task performance. Other mechanisms such as visual impairment, disrupted balance, and increased vibration are also likely to have contributed to the degradation. All of the mechanisms are directly or indirectly associated with the sway of the human body. While Chapter 6 presented the activation levels of the leg muscles primarily involved in maintaining balance and supported the idea that the frequency effects are associated with the resonant characteristics of the human body, additional evidence is needed to ascertain the contributions of other suggested mechanisms. Furthermore, previous studies suggest that the human body uses ankle strategy, hip strategy, and/or other postural control strategies to respond to external stimulations (for example Alexandrov et al., 2005; Alexandrov et al., 2001a, 2001b; Shin et al., 2006). As using different postural control strategies involves the movements of different joints such as the hip, knees, and/or ankles for maintaining balance, it is reasonable to believe that the effects of using different postural control strategies would be significant on manual task performance degradation. As such, further studies are needed to measure the body sway information at the head, shoulders, the hand holding the laser point, hip, knee, and ankles, relative to the floor motion, to ascertain the contributions of the mechanisms and the effects of using different postural control strategies on manual task performance degradations.

Body sway information can also provide supporting evidence to explain the unresolved questions raised in Chapter 6. Chapter 6 showed that the normalised leg muscle activation levels in high sopite syndrome severity participants were higher than the low sopite syndrome severity participants when they were performing the manual task. According to Postural Instability Theory which posits that “prolonged postural instability is the cause of motion sickness” (Riccio and Stoffregen, 1991, p. 231), it is reasonable to assume that the high sopite syndrome severity participants would have swayed more and used higher activation levels for maintaining balance and/or performing a manual task than the low sopite syndrome severity participants. Based on the results of this thesis, however, the validity of this assumption has yet to be confirmed. Furthermore, the normalised activation levels of both high and low sopite syndrome severity participants were similar when they were not performing the manual task. This may be because the high sopite syndrome severity participants allowed their body to sway more than the low sopite syndrome severity participants. Measurements of body sway, with and without performing the CTT, are required to answer these questions.

7.2.7 Reproduce the manual task performance investigation in wind-excited buildings

Chapter 5 suggested that sopite syndrome may act as a stressor that intervened in allocating attentional resources for performing a manual task and/or cognitive processes of other activities. Since the attentional resource capacity of an individual is limited, the occurrence of sopite syndrome and/or carrying out other activities may push the individual to perform the manual task in the near over-loaded zone or even over-loaded zone. In a controlled laboratory environment, the participants only needed to perform the CTT; the attentional resources used for cognitive processes of other activities were limited. This reduces the requirement on the attentional resource capacity. However, occupants in wind excited building environments are like to concurrently perform multiple tasks that demand a large amount of attentional resources. These tasks may act like additional distractions that push the occupants to perform in near-overloaded or overloaded zones. Therefore, the results of this thesis may underestimate the effects of sopite syndrome on manual task performance. Further studies may reproduce the experiment used in this thesis in wind-excited building environments to investigate the interaction effects of sopite syndrome and cognitive processes of other activities on manual task performance. Data collected from wind-excited building environments at selected frequencies and acceleration magnitudes can be used to validate the data controlled from laboratory environments.

7.2.8 Participants

Serviceability criteria for assessing the acceptability of wind-induced building motion should be aimed at buildings used by the general public. Therefore, the data used to establish the serviceability criteria should be collected from a group of participants that fit with the demographic information of the general public. However, the participants of this thesis were all young, healthy and fit university students with a mean age of 21 years, which is much lower than the mean age of the general public. Hence further studies are needed to investigate the effects of motion on manual task performance of participants that are representative of the general public. Furthermore, effects of other personal factors such as individual personality and motivation may be significant on performance (for example Graybiel et al., 1965; Webb et al., 1981). Thus further studies should also consider the effects of personal factors on manual task performance.

7.3 Concluding remarks

Over the last 50 years, studies have been conducted to investigate the habitability of wind-excited buildings. A majority of the studies have focused on the perception thresholds and/or tolerance of occupants to wind-induced building motion. The current criteria and recommendations for assessing the acceptability of wind-induced motion of buildings used for general purposes were established largely based on results of the studies, that is, the perception thresholds and/or tolerance to the motion.

This thesis demonstrates that low-frequency, low-acceleration motion that are comparable to wind-induced building motion degrades manual task performance; the current criteria and recommendations are insufficient to thoroughly assess the acceptability of wind-induced building motion on all human responses in wind-excited buildings. The performance degradation is related to motion frequency and acceleration, sopite syndrome, and the activities of leg muscles involved in maintaining balance.

The study results indicate the effects of these factors on manual task performance in wind-excited building environments are intertwined. The mechanisms causing manual task performance degradation may be even more complicated. It is likely to involve other physiological and/or psychological factors that were not considered in this thesis. In addition, these factors may also adversely affect other responses of occupants in wind-excited buildings. Looking forward, further multi-disciplinary studies are needed to fully explore, understand, and mitigate the adverse effects of wind-induced building motion on all human responses such that the habitability of wind-excited buildings is improved.

REFERENCE

- 3M™ Red Dot™ Adult Solid Gel Electrode 2238. (n.d.).
- Alexandrov, A. V, Frolov, A. A., Horak, F., Carlson-Kuhta, P., & Park, S. (2005). Feedback equilibrium control during human standing. *Biological Cybernetics*, 93(5), 309–322. <https://doi.org/10.1007/s00422-005-0004-1>
- Alexandrov, A. V, Frolov, A. A., & Massion, J. (2001a). Biomechanical analysis of movement strategies in human forward trunk bending. I. Modeling. *Biological Cybernetics*, 84(6), 425–434. <https://doi.org/10.1007/PL00007986>
- Alexandrov, A. V, Frolov, A. A., & Massion, J. (2001b). Biomechanical analysis of movement strategies in human forward trunk bending. II. Experimental study. *Biological Cybernetics*, 84(6), 435–443. <https://doi.org/10.1007/PL00007987>
- Allen, R. W., Jex, H. R., & Magdaleno, R. E. (1973). *Manual control performance and dynamic response during sinusoidal vibration.*
- Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin*, 58(1), 135–139. [https://doi.org/10.1016/S0361-9230\(02\)00770-0](https://doi.org/10.1016/S0361-9230(02)00770-0)
- Architectural Institute of Japan. (2004). *Guidelines for the evaluation of habitability to building vibration, AIJ-GEH-2004.* Tokyo, Japan.
- Australian Standard/New Zealand Standard. (2011). Structural design actions - Part 2 : Wind Actions, 2, 1–101.
- Bio Amp Cables | ADInstruments. (n.d.). Retrieved March 4, 2016, from <http://www.adinstruments.com/products/bio-amp-cables>
- Bio Amps | ADInstruments. (n.d.). Retrieved March 4, 2016, from <http://www.adinstruments.com/products/bio-amps>

- Biopotential Electrodes and Lead Wires | ADInstruments. (n.d.). Retrieved March 4, 2016, from <http://www.adinstruments.com/products/biopotential-electrodes-and-lead-wires>
- Bourne, L. E., & Yaroush, R. A. (2003). *Stress and Cognition: A Cognitive Psychological Perspective (NASA/CR-2003-212282)*.
- Burton, M. D., Hitchcock, P. A., Kwok, K. C. S., & Roberts, R. D. (2005). Acceptability curves derived from motion simulator investigations and previous experience with building motion. In *10th Americas Conference on Wind Engineering*. Baton Rouge, Louisiana.
- Burton, M. D., Kwok, K. C. S., & Hitchcock, P. A. (2011). Effect of low frequency motion on the performance of a dynamic manual tracking task. *Wind and Structures, An International Journal*, 14(6), 517–536.
- Burton, M. D., Kwok, K. C. S., Hitchcock, P. A., & Denoon, R. O. (2006). Frequency Dependence of Human Response to Wind-Induced Building Motion. *Journal of Structural Engineering*, 132(2), 296–303. [https://doi.org/10.1061/\(ASCE\)0733-9445\(2006\)132:2\(296\)](https://doi.org/10.1061/(ASCE)0733-9445(2006)132:2(296))
- Campbell, S., Kwok, K. C. S., & Hitchcock, P. A. (2005). Dynamic characteristics and wind-induced response of two high-rise residential buildings during typhoons. *Journal of Wind Engineering and Industrial Aerodynamics*, 93(6), 461–482. <https://doi.org/10.1016/j.jweia.2005.03.005>
- Chen, P. W., & Robertson, L. E. (1972). Human perception thresholds of horizontal motion. *Journal of Structural Division, ASCE*, 98(ST8), 1681–1695.
- Chong, R. K. Y., Mills, B., Dailey, L., Lane, E., Smith, S., & Lee, K. H. (2010). Specific interference between a cognitive task and sensory organization for stance balance control in healthy young adults: Visuospatial effects. *Neuropsychologia*, 48(9), 2709–2718. <https://doi.org/10.1016/j.neuropsychologia.2010.05.018>

- Clark, B., & Graybiel, A. (1961). Human performance during adaptation to stress in the Pensacola slow rotation room. *Aerospace Medicine*, 32(2), 93–106. Retrieved from http://www.ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19730024279_1973024279.pdf
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences (2nd ed.)*. Hillsdale, N.J: L. Erlbaum Associates.
- Coyle, D. C. (1931). Relation between motion and sensation. *Civil Engineering*, 1(8), 700–701.
- Day, J. T., Lichtwark, G. a, & Cresswell, A. G. (2013). Tibialis anterior muscle fascicle dynamics adequately represent postural sway during standing balance. *Journal of Applied Physiology*, 115(12), 1742–1750. <https://doi.org/10.1152/jappphysiol.00517.2013>
- De Luca, C. J. (2002). *Surface electromyography : detection and recording*. DelSys Incorporated.
- Denoon, R. O. (2000). *Designing for Wind-Induced Serviceability Accelerations in Buildings*. The University of Queensland.
- Denoon, R. O., Kwok, K. C. S., & Roberts, R. D. (2001). The Use of Motion Simulators in the Investigation of Occupant Response to Wind-Induced Building Motion. In *The fifth Asia-Pacific Conference on Wind Engineering* (pp. 97–100).
- Fitzpatrick, R. C., Gorman, R. B., Burke, D., & Gandevia, S. C. (1992). Postural proprioceptive reflexes in standing human subjects: bandwidth of response and transmission characteristics. *The Journal of Physiology*, 458, 69–83. https://doi.org/pdf/Fitzpatrick_etal_1992.pdf

- Gianaros, P. J., Muth, E. R., Mordkoff, J. T., Levine, M. E., & Stern, R. M. (2001). A questionnaire for the assessment of the multiple dimensions of motion sickness. *Aviation, Space, and Environmental Medicine*, 72(2), 115–119. Retrieved from <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2910410/>
- Golding, J. F. (1998). Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. *Brain Research Bulletin*, 47(5), 507–516. [https://doi.org/10.1016/S0361-9230\(98\)00091-4](https://doi.org/10.1016/S0361-9230(98)00091-4)
- Golding, J. F. (2006). Motion sickness susceptibility. *Autonomic Neuroscience: Basic & Clinical*, 129(1–2), 67–76. <https://doi.org/10.1016/j.autneu.2006.07.019>
- Golding, J. F., & Kerguelen, M. (1992). A comparison of the nauseogenic potential of low frequency vertical versus horizontal linear oscillation. *Aviation Space and Environmental Medicine*, 63(6), 491–497. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/1520219>
- Goto, T. (1983). Studies on wind-induced motion of tall buildings based on occupants' reactions. *Journal of Wind Engineering and Industrial Aerodynamics*, 13, 241–252.
- Goto, T., Iwasa, Y., & Tsurumaki, H. (1990). An experimental study on the relationship between motion and habitability in a tall residential building. In *Proceedings of tall buildings: 2000 and beyond, fourth world congress* (pp. 817–829). Hong Kong.
- Gray, H. (1918). *Anatomy of the human body* (The Bartle). Retrieved from <http://www.bartleby.com/107/>
- Graybiel, A., Kennedy, R. S., Knoblock, E. C., Guedry, F. E., Mertz, W., McLeod, M. E., ... Fregly, A. R. (1965). Effects of exposure to a rotating environment (10 RPM) on four aviators for a period of twelve days. *Aerospace Medicine*, 36, 733–754.

- Graybiel, A., & Knepton, J. (1976). Sopite syndrome: a sometimes sole manifestation of motion sickness. *Aviation, Space, and Environmental Medicine*, 47(8), 873–82.
- Guedry, F. E., Kennedy, R. S., Harris, C. S., & Graybiel, A. (1964). Human performance during two weeks in a room rotating at three rpm. *Aerospace Medicine*, 35, 1071–1082. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/14222393>
- Hammam, E., Hau, C. L. V., Wong, K.-S., Kwok, K. C. S., & Macefield, V. G. (2014). Vestibular modulation of muscle sympathetic nerve activity by the utricle during sub-perceptual sinusoidal linear acceleration in humans. *Experimental Brain Research*, 232(4), 1379–88. <https://doi.org/10.1007/s00221-014-3856-6>
- Hansen, R. J., Reed, J. W., & Vanmarcke, E. H. (1973). Human Response to Wind-Induced Motion of Buildings. *Journal of the Structural Division*, 99(7), 1589–1605. Retrieved from <http://cedb.asce.org/cgi/WWWdisplay.cgi?20329>
- Hwang, S., Tae, K., Sohn, R., Kim, J., Son, J., & Kim, Y. (2009). The Balance Recovery Mechanisms Against Unexpected Forward Perturbation. *Annals of Biomedical Engineering*, 37(8), 1629–1637. <https://doi.org/10.1007/s10439-009-9717-y>
- IBM Corp. (2012). IBM SPSS Statistics for Windows. Armonk, NY: IBM Corp.
- International Organization for Standardization. (1983). *Guide for the evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)*, ISO 2631.
- International Organization for Standardization. (1984). *Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures, to low-frequency horizontal motion (0.063 to 1 Hz)* ISO6897:1984. Geneva, Switzerland.

- International Organization for Standardization. (2007). *Bases for design of structures - Serviceability of buildings and walkways against vibration ISO/FDIS10137:2007(E)*. Geneva, Switzerland.
- Irwin, A. W. (1975). Human reactions to oscillations of buildings -- Acceptable limits. *Building International*, 8, 89–102.
- Irwin, A. W. (1978). Human response to dynamic motion of structures. *The Structural Engineer*, 56A(9), 237–244.
- Irwin, A. W. (1981). Perception, comfort and performance criteria for human beings exposed to whole body pure yaw vibration and vibration containing yaw and translational components. *Journal of Sound and Vibration*, 76(4), 481–497.
- Irwin, A. W., & Goto, T. (1984). Human perception, task performance and simulator sickness in single and multi-axis low frequency horizontal linear and rotational vibration. In *United Kingdom Informal Group Meeting on Human Response to Vibration* (pp. 289–313). Edinburgh.
- Isyumov, N. (1993). Criteria for Acceptable Wind-Induced Motions of Tall Buildings. In *International Conference on Tall Buildings, CTBUH*. Rio De Janeiro.
- Isyumov, N. (1995). Motion perception, tolerance and mitigation. In *The 5th world congress of the council on tall buildings and urban habitat* (pp. 1–19). Amsterdam, Netherlands.
- Isyumov, N., & Kilpatrick, J. (1996). Full-Scale Experience with Wind-Induced Motions of Tall Buildings. In *The 67th Regional Conference Council on Tall Buildings and Urban Habitat* (pp. 401–411). Chicago.
- Isyumov, N., Masciantonio, A., & Davenport, A. G. (1988). Measured motions of tall buildings in wind and their evaluation. In *Symposium/workshop on serviceability of buildings (movements, deformations, vibrations)* (pp. 181–199). University of Ottawa, Ottawa, Ontario, Canada.

- Jacob, R. G., Redfern, M. S., & Furman, J. M. (1995). Optic flow-induced sway in anxiety disorders associated with space and motion discomfort. *Journal of Anxiety Disorders*, 9(5), 411–425. [https://doi.org/10.1016/0887-6185\(95\)00021-F](https://doi.org/10.1016/0887-6185(95)00021-F)
- Jacob, R. G., WOODY, S. R., CLARK, D. B., LILIENFELD, S. O., HIRSCH, B. E., KUCERA, G. D., ... DURRANT, J. D. (1993). Discomfort With Space and Motion: A Possible Marker of Vestibular Dysfunction Assessed By the Situational Characteristics Questionnaire. *Journal of Psychopathology and Behavioral Assessment*, 15(4), 299–324. <https://doi.org/10.1007/BF00965035>
- Jeary, A. P., Morris, R. G., & Tomlinson, R. W. (1988). Perception of vibration - tests in a tall building. *Journal of Wind Engineering and Industrial Aerodynamics*, 29, 361–370.
- Kanda, J., Tamura, Y., & Fujii, K. (1988). Probabilistic criteria for human perception of low-frequency horizontal motions. In *Proceedings of Symposium/Workshop on Serviceability of Buildings* (pp. 260–269). Ottawa, Canada.
- Khan, F. R., & Parmelee, R. A. (1971). Service criteria for tall buildings for wind loading. In *Proceedings of 3rd International Conference on Wind Effects on Buildings and Structures* (pp. 401–407). Tokyo, Japan.
- Kim, Y. C., & Kanda, J. (2008). Wind response characteristics for habitability of tall buildings in Japan. *The Structural Design of Tall and Special Buildings*, 17(3), 683–718. <https://doi.org/10.1002/tal.373>
- Kojima, N., Goto, T., & Yamada, M. (1972). Human perception and the swaying state of the body (Part 1). In *Summaries of Technical Papers of Annual Meeting, Planning and Environmental Engineering* (pp. 495–496). Tokyo, Japan: Architectural Institute of Japan.
- Kwok, K. C. S., Burton, M. D., & Abdelrazaq, A. K. (2015). *Wind-Induced Motion of Tall Buildings: Designing for Habitability*. Reston, VA: American Society of Civil Engineers. <https://doi.org/10.1061/9780784413852>

- Kwok, K. C. S., & Hitchcock, P. A. (2008). Occupant comfort test using a tall building motion simulator. In *Proceedings of 4th International Conference on Advances in Wind and Structures*. Jeju Korea.
- Kwok, K. C. S., Hitchcock, P. A., & Burton, M. D. (2009). Perception of vibration and occupant comfort in wind-excited tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 97, 368–380. <https://doi.org/10.1016/j.jweia.2009.05.006>
- Lackner, J. R. (2014). Motion sickness: More than nausea and vomiting. *Experimental Brain Research*, 232(8), 2493–2510.
- Lamb, S. M., & Kwok, K. C. S. (2016). Sopite syndrome in wind-excited buildings: productivity and wellbeing impacts. *Building Research & Information*, 3218(June), 1–12. <https://doi.org/10.1080/09613218.2016.1190140>
- Lamb, S. M., Kwok, K. C. S., & Walton, D. (2013). Occupant comfort in wind-excited tall buildings: Motion sickness, compensatory behaviours and complaint. *Journal of Wind Engineering and Industrial Aerodynamics*, 119, 1–12. <https://doi.org/10.1016/j.jweia.2013.05.004>
- Lamb, S. M., Kwok, K. C. S., & Walton, D. (2014). A longitudinal field study of the effects of wind-induced building motion on occupant wellbeing and work performance. *Journal of Wind Engineering and Industrial Aerodynamics*, 133, 39–51. <https://doi.org/10.1016/j.jweia.2014.07.008>
- Lawson, B. D., & Mead, a. M. (1998). The sopite syndrome revisited: Drowsiness and mood changes during real or apparent motion. *Acta Astronautica*, 43(3–6), 181–192. [https://doi.org/10.1016/S0094-5765\(98\)00153-2](https://doi.org/10.1016/S0094-5765(98)00153-2)
- Lawther, A., & Griffin, M. J. (1988). Motion sickness and motion characteristics of vessels at sea. *Ergonomics*, 31(10), 1373–94. <https://doi.org/10.1080/00140138808966783>

- Lee, B. E. (1983). The perception of the wind-induced vibration of a tall building: A personal viewpoint. *Journal of Wind Engineering and Industrial Aerodynamics*, 12(3), 379–384. [https://doi.org/10.1016/0167-6105\(83\)90059-4](https://doi.org/10.1016/0167-6105(83)90059-4)
- Mathiesen, K. (2015). Where is the world's windiest city? Spoiler alert: it's not Chicago. Retrieved from <https://www.theguardian.com/cities/2015/oct/15/where-world-windiest-city-spoiler-alert-chicago-wellington>
- Matsangas, P., & McCauley, M. E. (2014). Sopite syndrome: A revised definition. *Aviation Space and Environmental Medicine*, 85(6), 672–673. <https://doi.org/10.3357/ASEM.3891.2014>
- Matsangas, P., McCauley, M. E., & Becker, W. (2014). The Effect of Mild Motion Sickness and Sopite Syndrome on Multitasking Cognitive Performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 56(6), 1124–1135. <https://doi.org/10.1177/0018720814522484>
- May, B., Tomporowski, P. D., & Ferrara, M. (2009). Effects of backpack load on balance and decisional processes. *Military Medicine*, 174(12), 1308–1312.
- McCauley, M. E., Royal, J. W., Wylie, C. D., O'Hanlon, J. F., & Mackie, R. R. (1976). *Motion Sickness Incidence: Exploratory Studies of Habituation, Pitch and Roll, and the Refinement of a Mathematical Model*. California. Retrieved from <http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA024709>
- McLeod, R. W., & Griffin, M. J. (1988). Performance of a complex manual control task during exposure to vertical whole-body vibration between 0.5 and 5.0 Hz. *Ergonomics*, 31(8), 1193–1203. <https://doi.org/10.1080/00140138808966757>
- McLeod, R. W., & Griffin, M. J. (1989). Review of the effects of translational whole-body vibration on continuous manual control performance. *Journal of Sound and Vibration*, 133(1), 55–115. [https://doi.org/10.1016/0022-460X\(89\)90985-1](https://doi.org/10.1016/0022-460X(89)90985-1)

- McLeod, R. W., & Griffin, M. J. (1993). Effects of duration and vibration on performance of a continuous manual control task. *Ergonomics*, 36(6), 645–659. <https://doi.org/10.1080/00140139308967926>
- McLeod, R. W., & Griffin, M. J. (1995). Mechanisms of vibration-induced interference with manual control performance. *Ergonomics*, 38(7), 1431–1444. <https://doi.org/10.1080/00140139508925200>
- Melbourne, W. H. (1975). Cross-wind response of structures to wind action. In *4th International Conference on Wind Effects on Buildings and Structures* (pp. 343–358). London.
- Melbourne, W. H. (1977). Probability distributions associated with the wind loading of structures. *Institution of Engineers (Australia) Civ Eng Trans*, CE19(1), 58–67.
- Melbourne, W. H., & Cheung, J. (1988). Designing for serviceable accelerations in tall buildings. In *4th International Conference on Tall Buildings* (pp. 148–155). Hong Kong and Shanghai.
- Melbourne, W. H., & Palmer, T. R. (1992). Accelerations and comfort criteria for buildings undergoing complex motions. *Journal of Wind Engineering and Industrial Aerodynamics*, 41(1–3), 105–116. [https://doi.org/10.1016/0167-6105\(92\)90398-T](https://doi.org/10.1016/0167-6105(92)90398-T)
- Mersmann, F., Bohm, S., Bierbaum, S., Dietrich, R., & Arampatzis, A. (2013). Young and old adults prioritize dynamic stability control following gait perturbations when performing a concurrent cognitive task. *Gait and Posture*, 37(3), 373–377. <https://doi.org/10.1016/j.gaitpost.2012.08.005>
- Money, K. (1970). Motion Sickness. *Physiological Reviews*, 50(1), 1–39.

- Nakamura, O., Goto, T., Ishikawa, T., Ohkuma, T., Suzuki, M., & Tamura, Y. (2004). Comments of “AIJ guidelines for the evaluation of habitability to wind-induced vibration.” In *WERC International Symposium on Architectural Wind Engineering* (pp. 61–70).
- Nakata, S., Tamura, Y., & Otsuki, T. (1993). Habitability under horizontal vibration of low rise buildings. In *International Colloquium, Structural Serviceability of Buildings, IABSE Reports* (pp. 39–44). Goteberg, Sweden.
- Noguchi, K., Hiwatashi, K., Kobayashi, A., Tsujita, O., & Goto, T. (1993). Human response to horizontal motion of tall buildings. In *International Colloquium, Structural Serviceability of Buildings, IABSE Reports* (Vol. 69, pp. 53–58). Goteberg, Sweden.
- O’Hanlon, J. F., & McCauley, M. E. (1973). *Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion*. California.
- Pacheco-Unguetti, A. P., Acosta, A., Callejas, A., & Lupianez, J. (2010). Attention and Anxiety: Different Attentional Functioning Under State and Trait Anxiety. *Psychological Science*, 21(2), 298–304.
<https://doi.org/10.1177/0956797609359624>
- picture-of-the-ankle. (2014). Retrieved July 4, 2016, from <http://www.webmd.com/fitness-exercise/picture-of-the-ankle>
- PowerLab | ADInstruments. (n.d.). Retrieved March 4, 2016, from <http://www.adinstruments.com/products/powerlab>
- Reason, J. T., & Brand, J. J. (1975). *Motion sickness*. Academic Press Inc. (London) Limited.
- Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology*, 3(3), 195–240.

- Shin, Y., Fard, M., Inooka, H., & Kim, I. H. (2006). Human Postural Dynamics in Response to the Horizontal Vibration. *International Journal of Control, Automation, and Systems*, 4(3), 325–332. Retrieved from http://ijcas.com/admin/paper/files/IJCAS_v4_n3_pp.325-332_.pdf
- Shioya, K., & Kanda, J. (1993). Human Perception Thresholds of Horizontal Motion. In *International Colloquium, Structural Serviceability of Buildings, IABSE Reports* (pp. 45–52). Goteberg, Sweden.
- Shioya, K., Kanda, J., Tamura, Y., & Fujii, K. (1992). Human perception thresholds of two dimensional horizontal motion. In *ASCE Structures Congress* (pp. 480–483). San Antonio, USA.
- Stoffregen, T. A., Chen, F. C., Varlet, M., Alcantara, C., & Bardy, B. G. (2013). Getting Your Sea Legs. *PLoS ONE*, 8(6). <https://doi.org/10.1371/journal.pone.0066949>
- Stoffregen, T. A., & Smart, L. J. (1998). Postural instability preceedes motion sickness. *Brain Research Bulletin*, 47(5), 437–448.
- Stoffregen, T. A., Yoshida, K., Villard, S., Scibora, L., & Bardy, B. G. (2010). Stance Width Influences Postural Stability and Motion Sickness. *Ecological Psychology*, 22(3), 169–191. <https://doi.org/10.1080/10407413.2010.496645>
- Tamura, Y., & Kareem, A. (Eds.). (2014). *Advanced Structural Wind Engineering* (Vol. 49). <https://doi.org/10.1007/978-4-431-54337-4>
- Tamura, Y., Kawana, S., Nakamura, O., Kanda, J., & Nakata, S. (2006). Evaluation perception of wind-induced vibration in buildings. *Proceedings of Institution of Civil Engineers: Structures & Buildings*, 159(October), 283–293.
- Walton, D., Lamb, S. M., & Kwok, K. C. S. (2011). A review of two theories of motion sickness and their implications for tall building motion sway. *Wind and Structures, An International Journal*, 14(6), 499–515. <https://doi.org/10.12989/was.2011.14.6.499>

- Webb, R. D. G., Bennett, M. D., Farmilo, B., Cole, S. H., Page, S. J., & Withey, W. R. (1981). Personality and inter-subject differences in performance and physiological cost during whole-body vibration. *Ergonomics*, 24(4), 245–255.
- Wertheim, A. H. (1998). Working in a moving environment. *Ergonomics*, 41(12), 1845–1858. <https://doi.org/10.1080/001401398186018>
- Winter, D. (1995). Human balance and posture control during standing and walking. *Gait & Posture*, 3(4), 193–214. [https://doi.org/10.1016/0966-6362\(96\)82849-9](https://doi.org/10.1016/0966-6362(96)82849-9)
- Wright, M. S., Bose, C. L., & Stiles, A. D. (1995). The incidence and effects of motion sickness among medical attendants during transport. *The Journal of Emergency Medicine*, 13(1), 15–20. [https://doi.org/10.1016/0736-4679\(94\)00106-5](https://doi.org/10.1016/0736-4679(94)00106-5)
- Yu, Y., Yank, J. R., Katsumata, Y., Villard, S., Kennedy, R. S., & Stoffregen, T. A. (2010). Visual vigilance performance and standing posture at sea. *Aviation Space and Environmental Medicine*, 81(4), 375–382. <https://doi.org/10.3357/ASEM.2638.2010>
- Yu, Y., Yank, J. R., Villard, S., & Stoffregen, T. A. (2010). Postural activity and visual vigilance performance during rough seas. *Aviation Space and Environmental Medicine*, 81(9), 843–849. <https://doi.org/10.3357/ASEM.2768.2010>

APPENDIX A

GENERAL INFORMATION FORM

Age	
Sex	
Dominant eye (Left / right)	
Vision problems (Normal / short-sighted / long-sighted / Astigmatisms / others)	
Colour blind (yes / no)	
How many hours did you sleep last night	
When was your last meal?	
When was your last caffeine intake?	
How often do you use computer? (Daily / Weekly / Occasionally)	
Which hand do you use when using the mouse? (Left / right)	

APPENDIX B

MOTION SICKNESS ASSESSMENT QUESTIONNAIRE (MSAQ)

Using the scale below, please rate how accurately the following statements describe your experience right now.

1 is for not at all

9 is for severely

Motion Sickness Assessment Questionnaire (MSAQ)

Statements	Rate
1. I felt sick to my stomach	
2. I felt faint-like	
3. I felt annoyed/irritated	
4. I felt sweaty	
5. I felt queasy	
6. I felt lightheaded	
7. I felt drowsy	
8. I felt clammy / cold sweat	
9. I felt disoriented	
10. I felt tired/fatigued	
11. I felt nauseated	
12. I felt hot/warm	
13. I felt dizzy	
14. I felt like I was spinning	
15. I felt as if I may vomit	
16. I felt uneasy	

APPENDIX C

CHANGES IN MOTION SICKNESS ASSESSMENT QUESTIONNAIRE SOPITE-RELATED AND CENTRAL SUBSCALE SCORES

Table C.1 Changes of Motion Sickness Assessment Questionnaire (MSAQ) sopite-related subscale score of all test participants.

Group	Subject code	Change of MSAQ sopite-related subscale score	Group	Subject code	Change of MSAQ sopite-related item score
1	LA3	-22.23	2	LA31	5.56
1	FA17	-13.89	2	LA2	8.33
1	FA1	-2.78	2	LA28	8.33
1	LA30	-2.78	2	FA12	8.33
1	FA2	0.00	2	FA25	8.33
1	FA3	0.00	2	FA18	13.89
1	FA4	0.00	2	FA10	13.89
1	FA5	0.00	2	LA20	13.89
1	FA20	0.00	3	LA24	16.67
1	FA23	0.00	3	FA14	16.67
1	FA24	0.00	3	LA14	19.44
1	LA11	0.00	3	LA25	19.44
1	FA8	2.78	3	LA1	19.44
1	FA22	2.78	3	FA11	19.45
1	LA9	2.78	3	FA19	19.45
1	LA22	2.78	3	LA5	19.45
2	LA26	5.55	3	LA29	19.45
2	LA33	5.55	3	LA7	25.00
2	FA21	5.56	3	LA32	44.45
2	LA8	5.56	3	FA7	52.78

Table C.2 Changes of Motion Sickness Assessment Questionnaire (MSAQ) central item score of all test participants.

Group	Subject code	Change of MSAQ central item score	Group	Subject code	Change of MSAQ central item score
1	LA3	-11.11	2	LA22	2.23
1	FA22	-8.89	2	LA8	4.45
1	FA17	-8.88	2	LA33	4.45
1	FA24	-6.67	2	FA20	6.66
1	LA26	-6.67	2	FA8	6.67
1	FA14	-4.44	2	LA28	6.67
1	FA1	0.00	2	LA31	8.88
1	FA2	0.00	3	FA19	8.89
1	FA3	0.00	3	LA24	8.89
1	FA4	0.00	3	FA5	11.11
1	FA12	0.00	3	LA20	13.33
1	FA18	0.00	3	LA5	15.56
1	FA23	0.00	3	FA11	17.78
1	FA25	0.00	3	LA7	20.00
1	LA9	0.00	3	LA14	20.00
1	LA11	0.00	3	LA25	20.00
1	LA30	0.00	3	LA29	20.00
2	FA21	2.22	3	LA32	26.66
2	FA10	2.23	3	LA1	26.67
2	LA2	2.23	3	FA7	48.89

APPENDIX D

MOTION SICKNESS SUBSCALE SCORES OF PARTICIPANTS COMPLETED CTT UNDER FORE-AFT MOTION CONDITIONS

One-way repeated-measures ANOVAs show that exposure to low-frequency, low-acceleration motion significantly changes the sopite-related subscale score but not peripheral, central, and gastrointestinal, as shown in Table D.1. Exposure to the low-frequency, low-acceleration motion significantly increases the sopite-related subscale score from pre-test ($M = 18.194$, $SD = 9.726$) to post-test ($M = 25.556$, $SD = 17.674$), as shown in Figure D.1. The increase in the sopite-related subscale score equates to an effect size of 0.52 (Cohen's d).

Table D.1 A summary of statistical results of the one-way repeated-measures ANOVAs on changes in motion sickness subscale scores.

Subscale score	<i>F</i>	<i>p-value</i>
Sopite-related	$F(1, 19) = 5.871$	$= 0.026$
Peripheral	$F(1, 19) = .417$	$= 0.526$
Central	$F(1, 19) = 1.842$	$= 0.191$
Gastrointestinal	$F(1, 19) = .054$	$= 0.818$

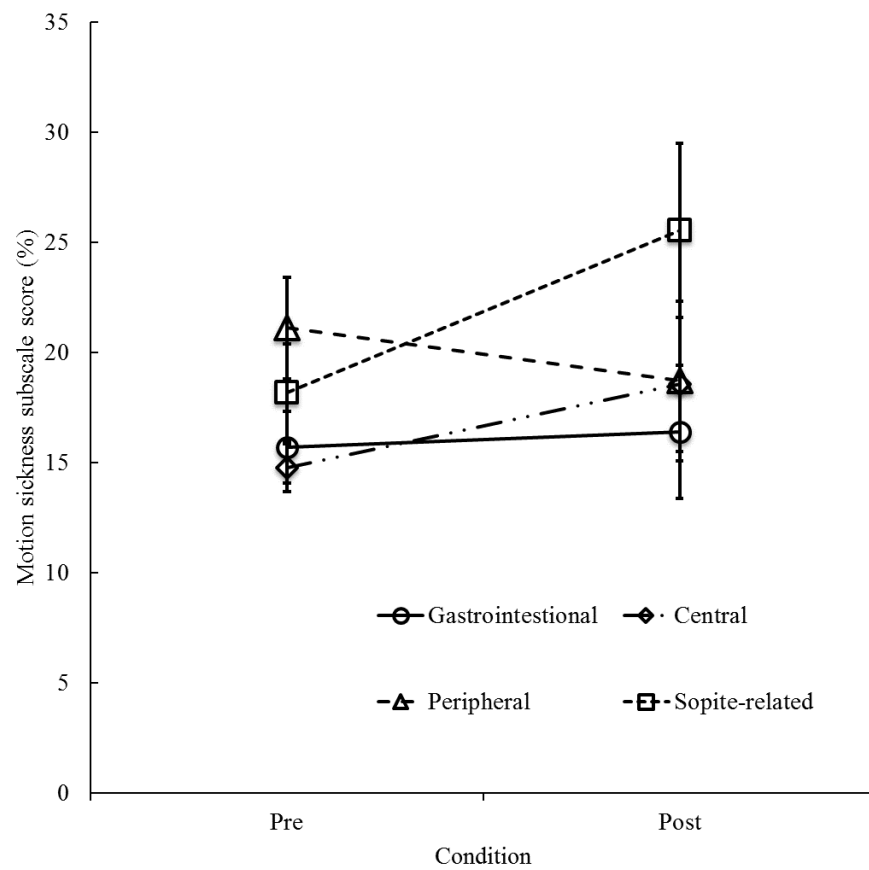


Figure D.1 Pre-test and post-test sopite-related subscale scores (mean \pm S.E.) of participants ($N = 20$) performing the CTT.

APPENDIX E

GROUPING OF PARTICIPANTS COMPLETED CTT UNDER FORE-AFT MOTION CONDITIONS BASED ON SOPITE RELATE SUBSCALE SCORE

The 20 participants performing the CTT under fore-aft motion conditions were divided into two sopite syndrome severity groups: high ($N = 9$) and low ($N = 11$) based on changes in sopite-related subscale score, as shown in Figure E.1.

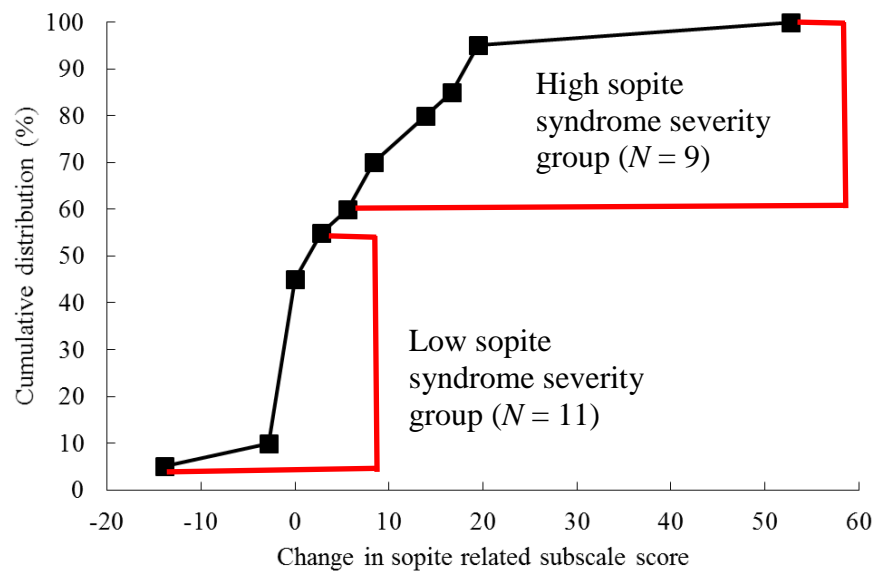


Figure E.1 Cumulative frequency distribution of change in sopite-related subscale score of participants performing the CTT under fore-aft motion conditions.

A mixed-design two-way ANOVA, with pre-post-test condition as the within-subjects factor and participants' sopite syndrome severity groups as the between-subjects factor, indicate that changes in sopite-related subscale score between sopite syndrome severity groups were significantly different, $F(1, 18) = 5.131$, $p\text{-value} < 0.036$. The sopite-related subscale score of the high sopite syndrome severity group increased from pre-test ($M = 19.444$, $SD = 9.921$) to post-test ($M = 37.037$, $SD = 14.487$) while that of the low sopite syndrome severity group of the pre-test ($M = 17.172$, $SD = 9.921$) and post-test ($M = 16.162$, $SD = 14.487$) were similar, as shown in Figure E.2. The increase in the sopite syndrome subscale score of the high sopite syndrome severity group from pre-test to post-test conditions equates to an effect size of 1.42 (Cohen's d).

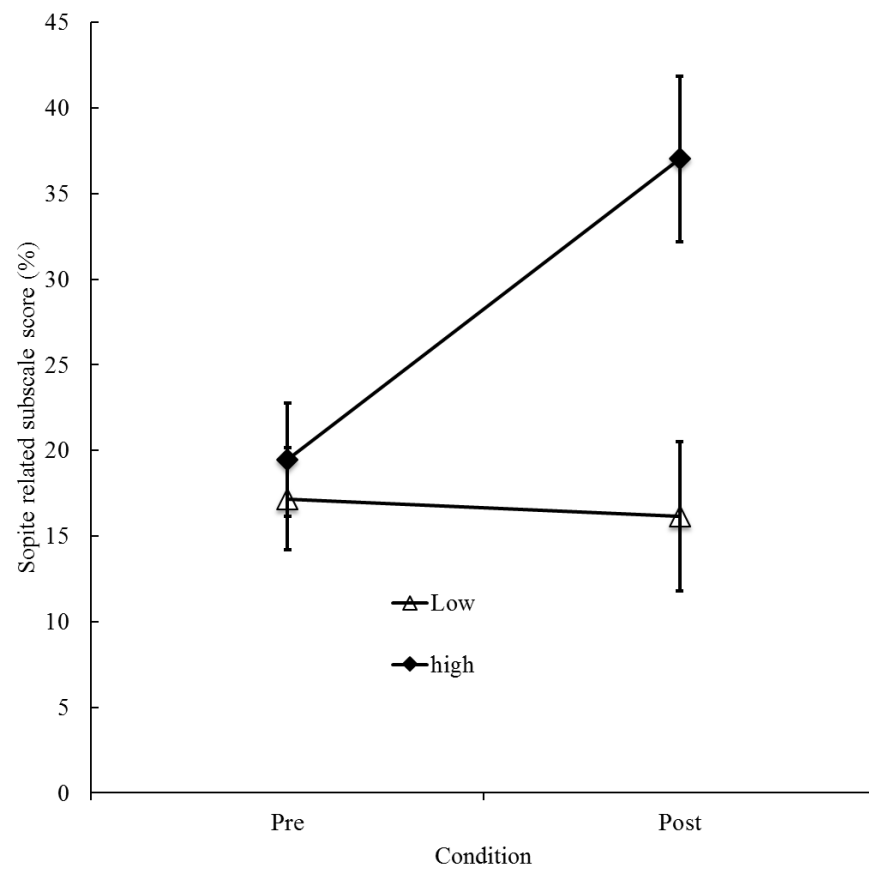


Figure E.2 Sopite-related subscale score (mean \pm S.E.) of high ($N = 9$) and low ($N = 11$) sopite syndrome severity groups of participants performing CTT under fore-aft motion conditions.